# Running and Optimizing Large Accelerators

*- Examples from the SLC, LEP, and LHC -*

Seminar SNS

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# Outline

- **Energy and Luminosity**
  The measure of success in particle physics
  Limitations and our job (the challenge)
- **SLC – Controlling collective effects in the linac**
  The linear collider
  The SLC linac beam (layout, beam movies)
  Wakefield emittance growth, Day-night effects, DFS
  The SLC team at SLAC
- **LEP – Beating the design**
  The LEP team at CERN
  Design and reality
  Vertical beam size optimization (luminosity)
  The super-conducting RF system (beam energy)
  Spin polarization of particle beams
  The unexpected I - IV
- **LHC – High intensity proton beams**
  The challenge of high beam power
  The beam cleaning and collimation system
- **Conclusion**

# Energy and Luminosity

Particle physics colliders: Produce new (and heavy) particles with … higher energy and luminosity!

E.g.: The Z boson $e^+ + e^- \rightarrow f + \bar{f}$

Beam energy E required to produce a Z boson:

$$M_Z = \left(E_{e^+} + E_{e^-}\right)/c^2 = 91.2\ \mathrm{GeV}$$

Rate of Z bosons produced: $R = \sigma \cdot L$

Cross section given by nature

Luminosity characterizes the accelerator perfor-mance! Improve…

*Example from the LEP-ALEPH detector*

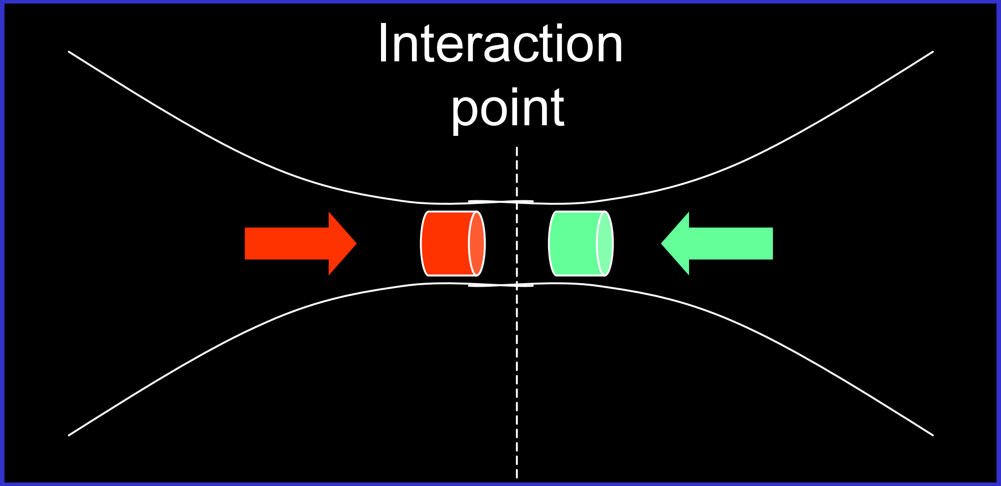
# Optimizing Collider Performance

Increase bunch current

$$L = \frac{i_b^2 \cdot n_b}{4\pi e^2 \cdot f_{rev} \cdot \sigma_x \cdot \sigma_y}$$

Reduce the beam sizes

| | |
|---|---|
| $i_b$ | Bunch current |
| $\sigma_x$ | Horizontal beam size at IP |
| $\sigma_y$ | Vertical beam size at IP |
| $n_b$ | Number of bunches |
| $f_{rev}$ | Revolution frequency |



# The Challenge

Typical problem:

Beam is disturbed by instabilities and unavoidable imperfections.

Beam size is blown-up (eventually intensity dependent).

Particles are lost along the accelerator (beam position or size).

The job for accelerator physicists:

Choose design such as to maximize performance (for reasonable cost).

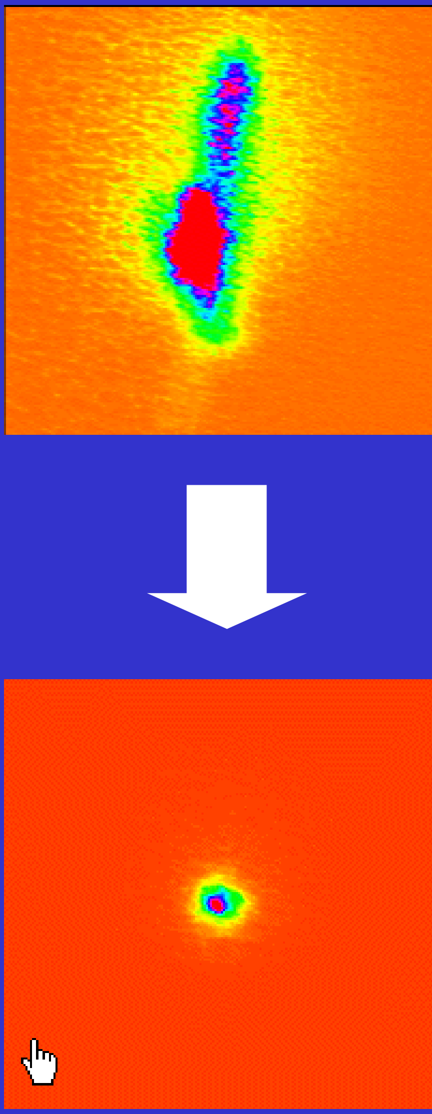
Specify tolerances for engineering and construction.

Measure and understand limitations.

Propose and implement solutions.

Success = Maximum performance in minimum time
(design gives basic measure)

Transverse profile
SLC linac beam



*(1.8 mm x 1.8 mm)*

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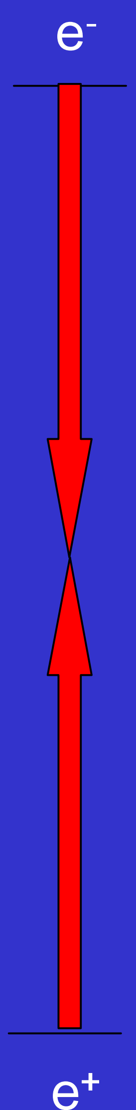
# The Linear Collider



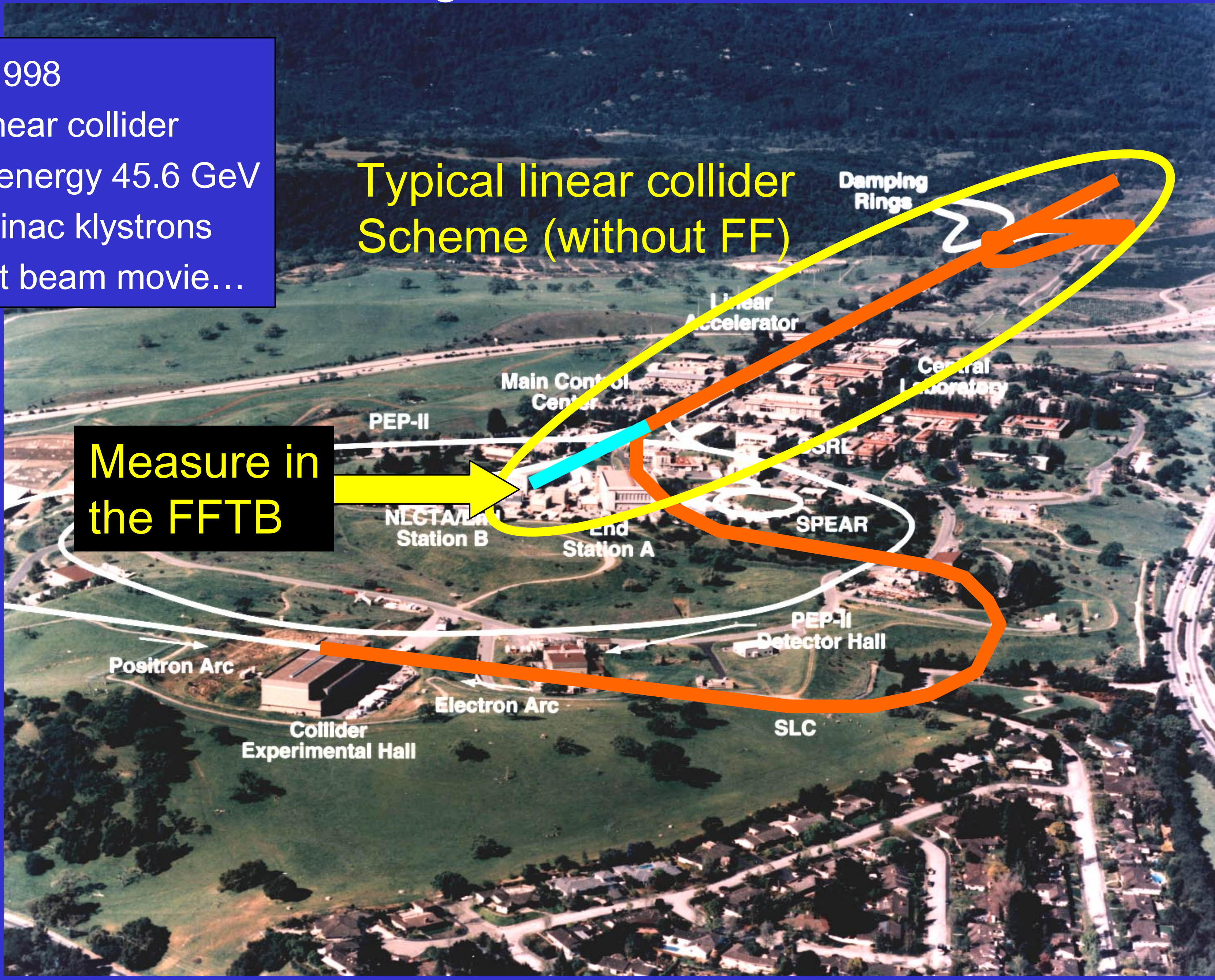

| | |
|---|---|
| Injectors | *Provide the beam* |
| Damping rings | *Provide small emittance* |
| Bunch compression | *Provide short bunch length* |
| Linear accelerator | *Provide beam energy* |
| Collimation | *Provide small background* |
| Final Focus | *Provide demagnification*<br>*Collide and dump beams* |
| Collimation | |
| Linear accelerator | |
| Bunch compression | |
| Damping rings | |
| Injectors | |

No design bending field
No synchrotron radiation
No multi-turn resonant effects

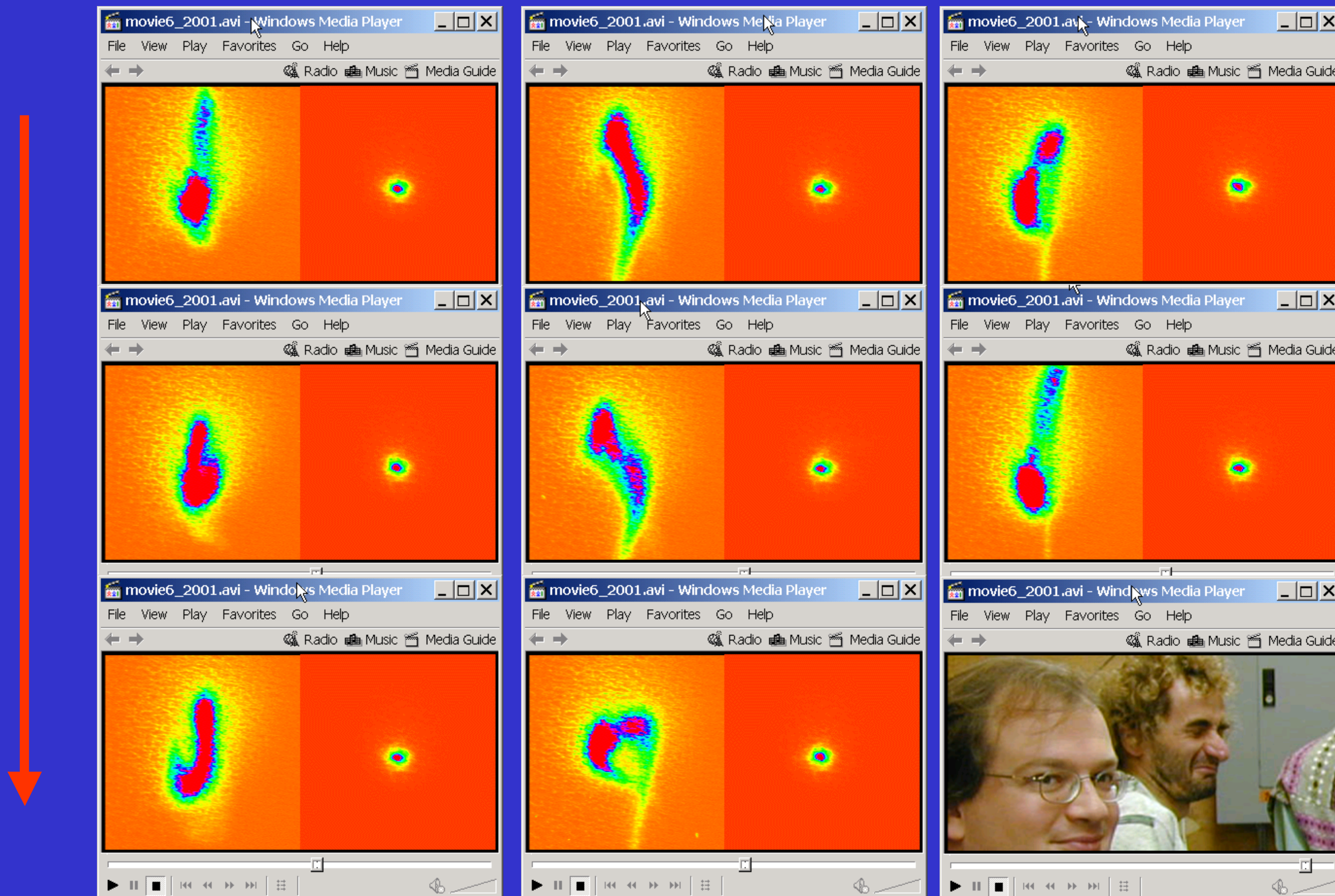
Limitations from circular colliders do not apply

# SLC – Controlling Collective Effects in the Linac

- 1989-1998
- First linear collider
- Beam energy 45.6 GeV
- ~ 240 linac klystrons
- Look at beam movie…



# Wakefield Tuning in the SLC



# Typical Features for SLC Linac Beams

- Low repetition rates (5-120 Hz)
- Small beam sizes (shown was smaller area than LEP)
- No equilibrium state, no damping after damping rings

  *Every pulse is different*

  *The beam is "living""*

- Asymmetric beam distributions, tails due to wakefields
- Intense tuning needed to control beam sizes and stability (much better for super-conducting linacs)
- Wakefield effects can be corrected very efficiently (took a while for SLC to learn how)
- Complete diagnostics is essential!

# Linac Emittance Growth

$$L_0 = \frac{N_e^2 \cdot N_b \cdot f_{rep}}{4\pi \ \sigma_x^* \cdot \sigma_y^*} \cdot H_D$$

with

$$\sigma_y^* = \sqrt{\beta_y^* \cdot \varepsilon_y}$$

Stability of emittance
Stability of optics

Emittance contributions:

$$\gamma\varepsilon_y \approx \gamma\varepsilon_y^{DR} + \Delta\gamma\varepsilon_y^{Design} + \underbrace{\Delta\gamma\varepsilon_y^{Linac} + \Delta\gamma\varepsilon_y^{FF}}$$

= 0

> 0

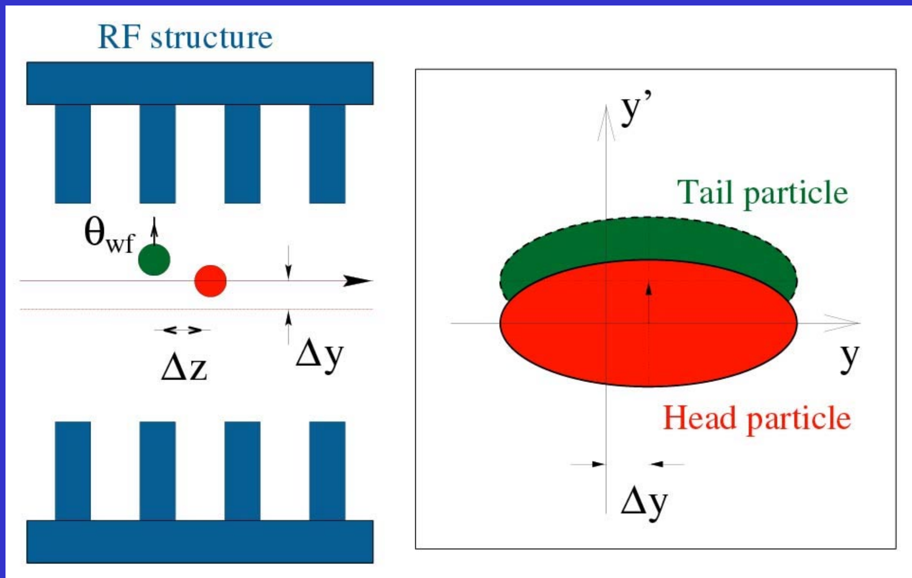
Perfectly straight trajectory (centered in all quadrupoles, structures and sextupoles along straight line)

Imperfect environment (magnet alignment errors, diagnostics errors) produces not-straight trajectory (dispersion, wakefields)

Transverse projected normalized emittance: Keep constant!

# Multi-Particle Beam Dynamics

Interaction: Accelerated charge ⟷ RF structures (small irises)




$$\theta_{wf} = W_t(\sigma_z)\cdot\frac{eN_e L_{struc}}{2E_0}\cdot\Delta y_1$$

R. Assmann
et al

THE LIAR LInear Accelerator Research PROJECT

Wakefield effect depends on:

Intra-bunch and inter-bunch wakefields
Offsets in rf structures (imperfections)
Longitudinal distribution
Charge
Energy
Optics
RF phases

Calculate effect with programs:

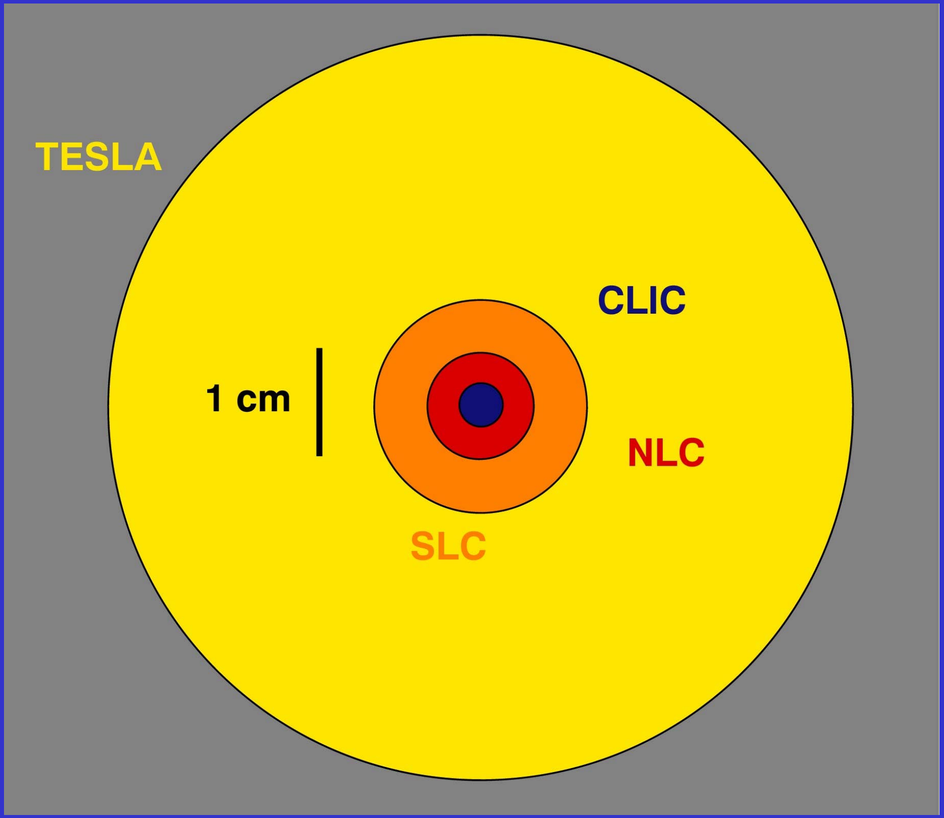
- Multi-particle beam dynamics
- Multiple interacting imperfections
- Chromatic, dispersive + wakefield errors
- Single-bunch and multi-bunch …

# Amplitude of Wakefields

Choice of technology determines radius of structure iris a:

High frequency – small a

Low frequency – large a



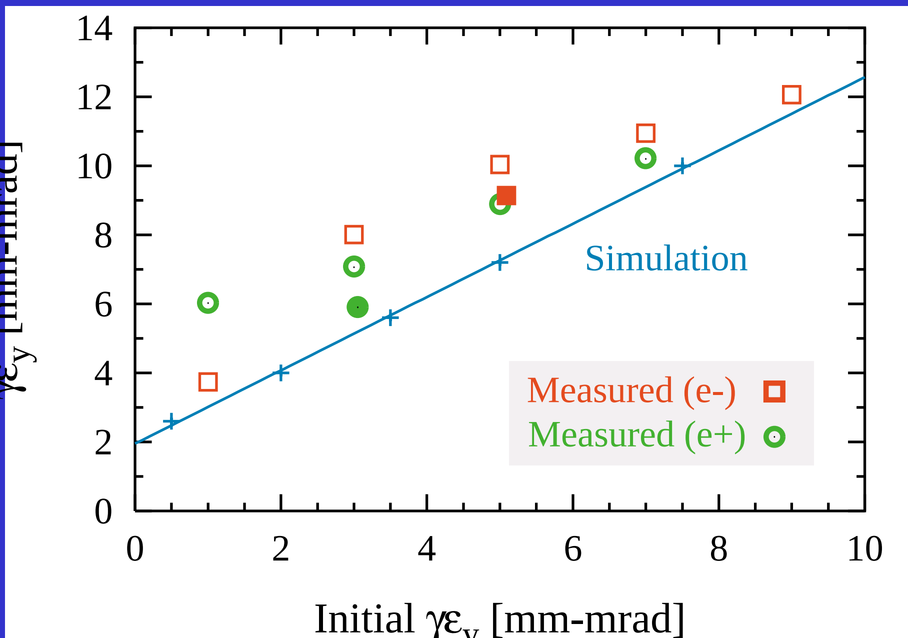

Stronger wakefields (beam induced electro-magnetic fields) with smaller iris radius!

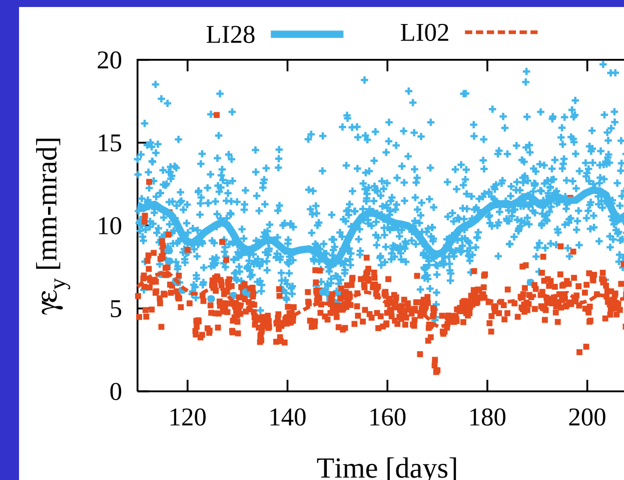
*Beam is closer to metallic walls…*

# SLC Wakefield Emittance Growth

Single bunch emittance growth (SLC 1996/1997):

R. Assmann, PAC97




$$\boxed{\gamma\varepsilon_{28} = \kappa \cdot \gamma\varepsilon_{\text{initial}} + \Delta\gamma\varepsilon_{\text{wf}}}$$

multiplicative additive

Simulation: $\kappa = 1.06$ $\Delta\gamma\varepsilon_{wf} = 2$

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*Problems due to poor emittance stability (drift towards larger emittances)*

Reasonable agreement with data from the SLC!

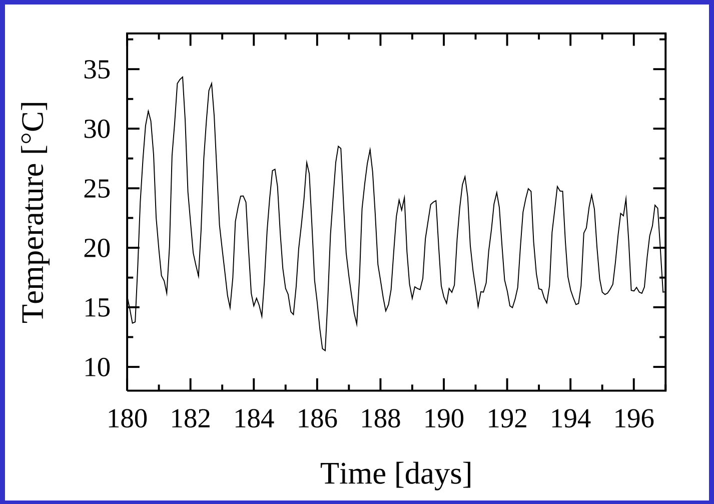
# SLC Day/Night Effects

Long-term day-night problem in the SLC:
Two reference set-ups (day/night)
Known to correlate with temperature.

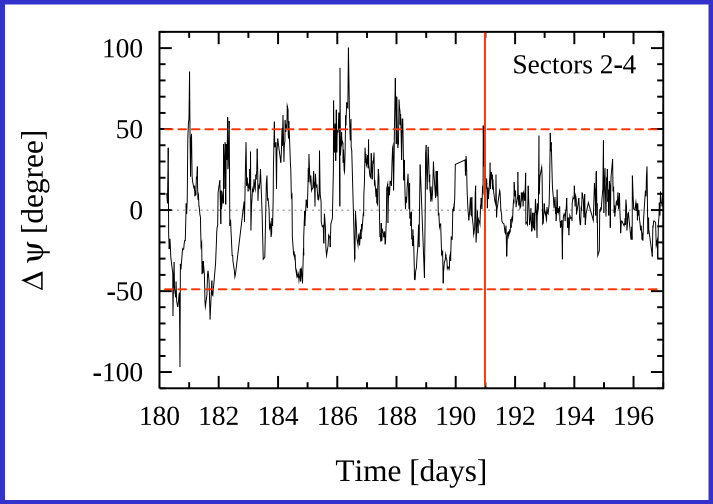
Problem analyzed with diagnostic pulse:
Measure optics versus time

Problem traced to:
Temperature dependent RF phase error
(travel klystron trigger signal over 3 km)
Once understood, corrected!

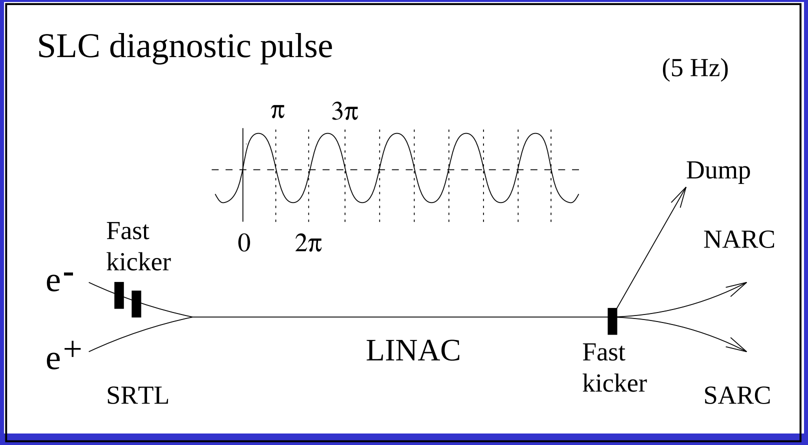
## Outside temperature




## Optics phase advance error




## Principle



# Dispersion-free Steering

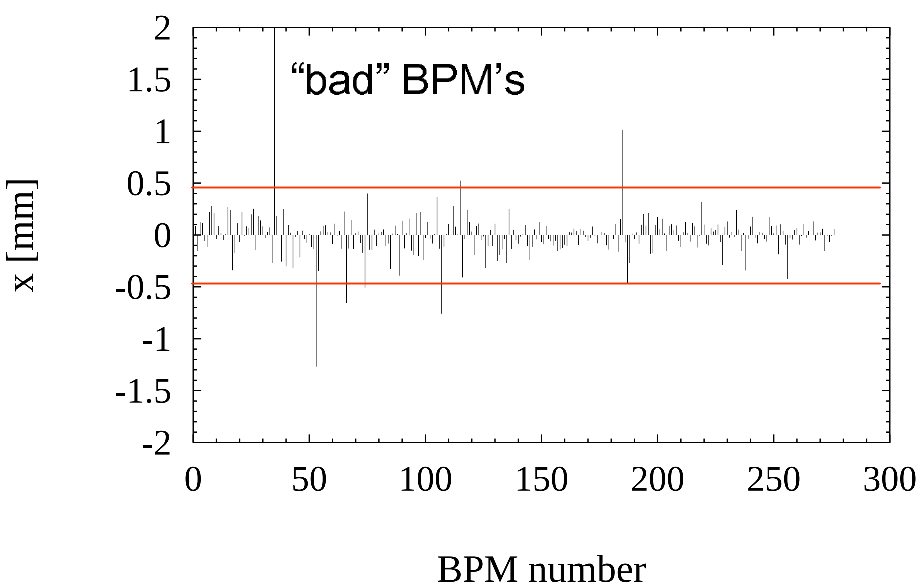
Any beam deflection $\theta$ depends on beam energy E: $\theta \sim 1/E$

Dispersion: Change in trajectory for change in energy!

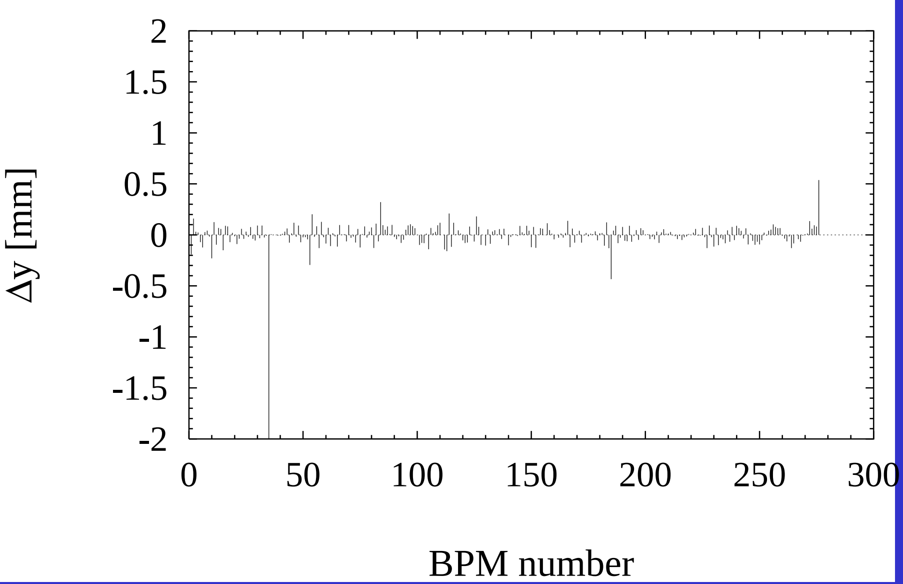
Only straight trajectory (no beam deflection) is dispersion-free!

SLC algorithm found trajectory with best performance:

Vertical Trajectory

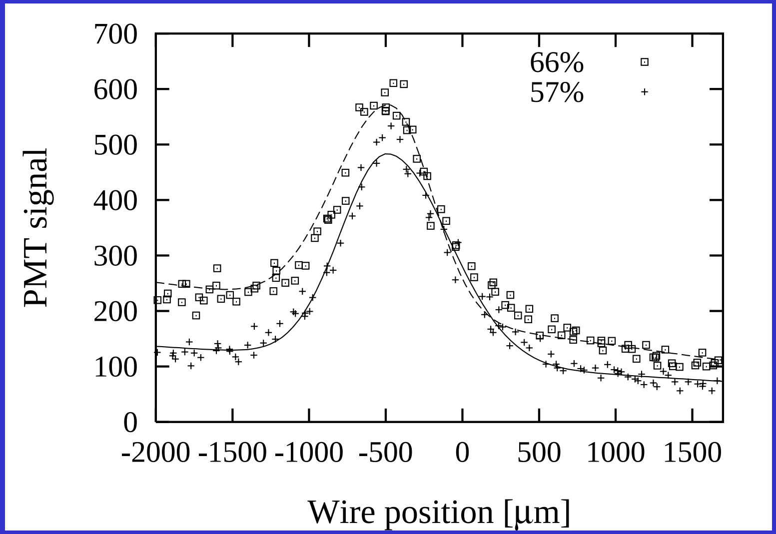



Vertical Dispersion

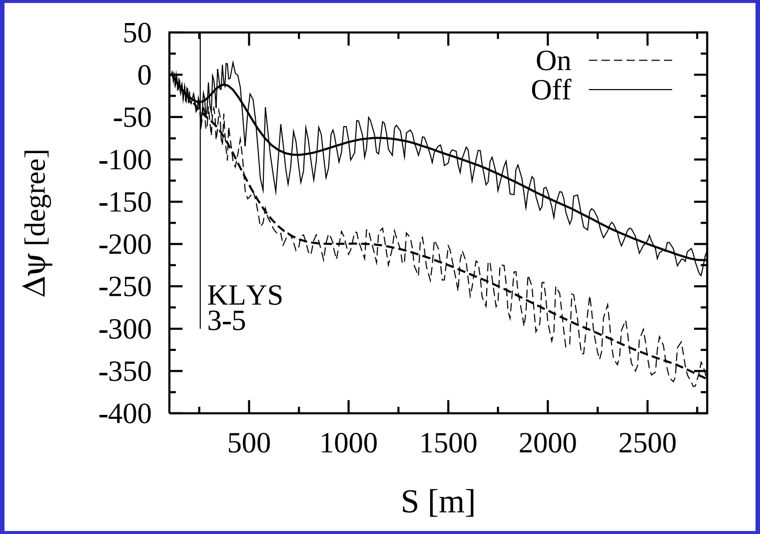


# Other SLC Worries

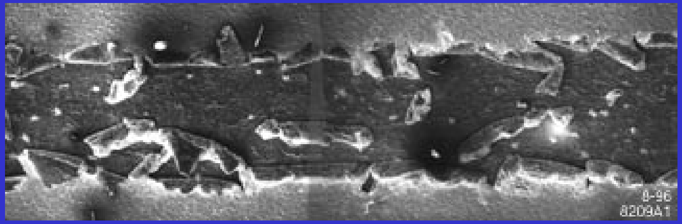
## Dark current



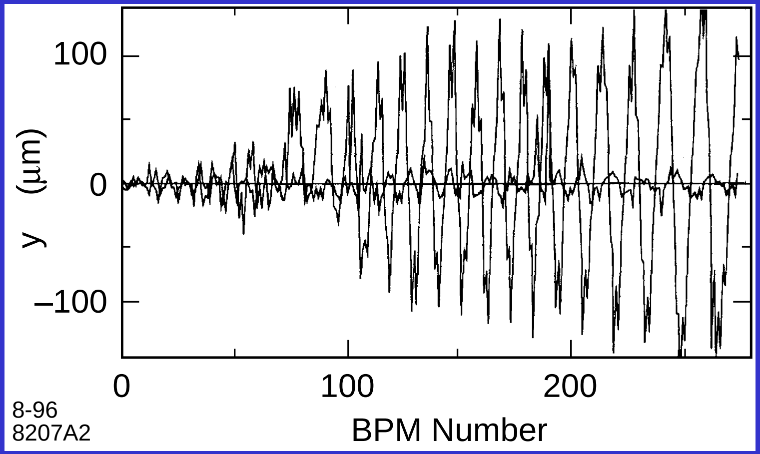

## Energy management




## Collimator damage




## Long-range wakefields



# The SLC Team at SLAC

**Operations group:**
People: ~ 10 staff
Main job: SLC
Duties: Shift work and routine operation

**Accelerator Research Departments:**
People: ~ 30 physicists
Main job: Various accelerators
Duties: Accelerator physics support, help in machine coordination

Daily control room meetings
“8 o’clock meeting” plus weekly program meetings.
Sub-system meetings…

*+ equipment groups*

**Accelerator Department:**
People: ~ 10 physicists
Main job: SLC
Duties: Machine coordination and optimization

Tendancy: 3 separate units
1. Theoretical AP
2. Applied AP
3. Operational unit

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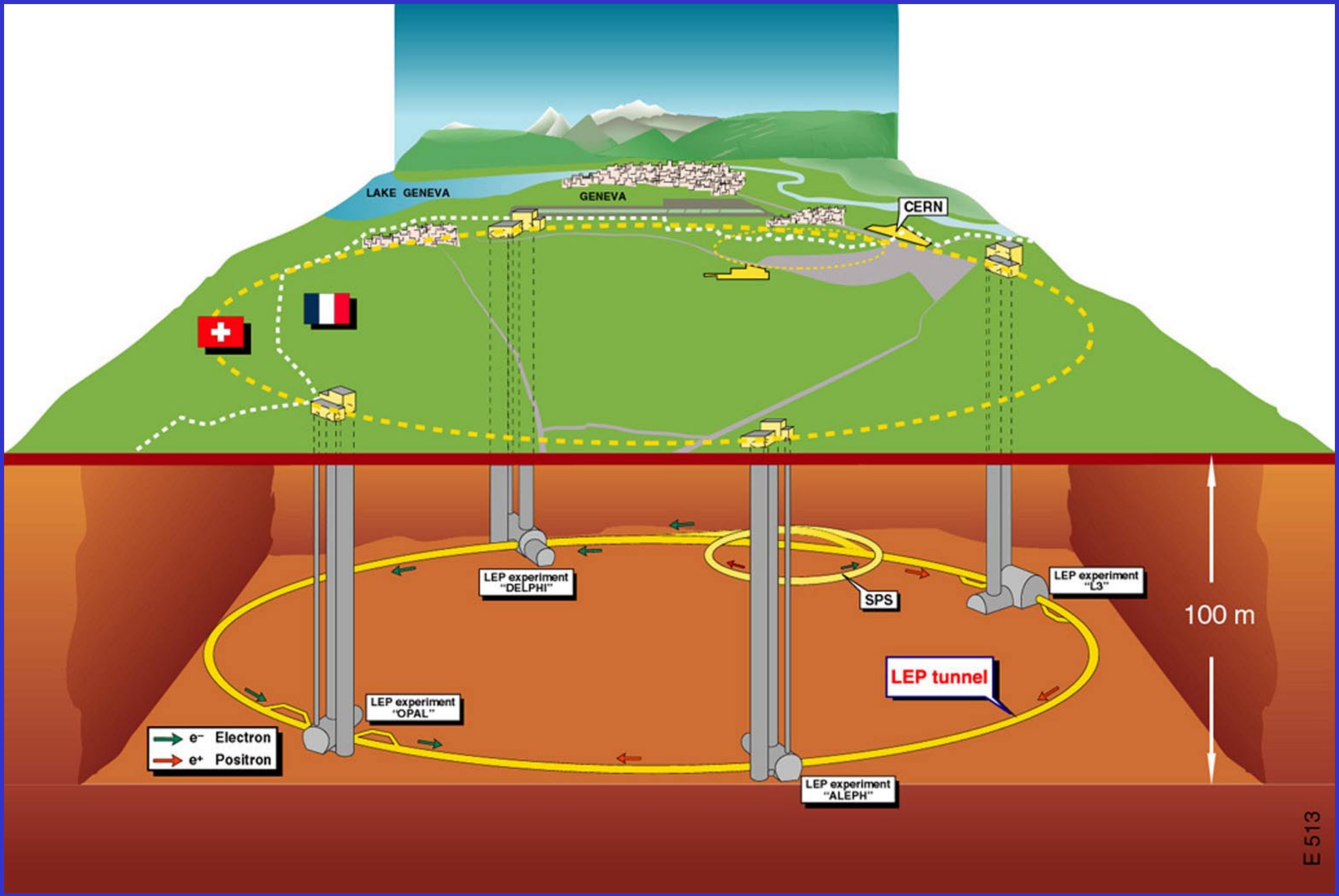
# The LEP Collider

LEP - The largest particle accelerator to date…

| | |
|---|---|
| 1989 | First turn |
| 1989-1995 | The Z-years (precision studies) |
| 1996-1999 | The W-years (precision studies) |
| 2000 | The Higgs-year (almost a discovery?) |
| Nov 2000 | Start of dismantling |

Circumference: 27 km

Energy range: 20 – 104.5 GeV




Tunnel up to ~100 m below ground. Injection from the SPS.

$e^+e^-$ collisions simultaneously in four interaction points.

# The LEP Team at CERN

Operations group:
People: GL, DGL
~ 8 physicists
~ 15 OP staff
Main job: SPS and LEP
Duties: Machine coordination, optimization, analysis, shift work and routine operation

Accelerator physics group:
People: ~ 15 physicists
Main job: Mainly LEP
Duties: Accelerator physics support, machine development

Project leader
Two weekly performance committee

*+ equipment groups*

Tradition: Engineer in Charge
Physicists hired in early part of career to take part in reduced shift schedule. Machine coordination after ~5 years. Transferred into other group after ~8 years. High profile CERN job.

Tendency: 2 main units
1. Theoretical AP
2. Combined applied AP and operational unit

# Overview CERN - SLAC

| | CERN | SLAC |
|---|---|---|
| Shift work | Operations staff + EIC (PhD physicist) every 3rd shift. EIC spends ~30-50% in the control room | Operations staff |
| Machine coord (on call) | Senior EIC | Accelerator physicists |
| Day-to day performance analysis and optimization | EIC's | Accelerator physicists |
| Machine development (performance upgrades) | Accelerator physicists + EIC's | Accelerator physicists |
| Design work | Accelerator physicists + support by EIC's | Accelerator physicists |

# The LEP Design

LEP was from the beginning conceived as:

Two-stage machine:

1) Z-physics at 91.2 GeV

2) W-physics at up to 100 GeV

+ anything new

Energy reach:

Magnets, power supplies, vacuum system, tunnel radius/length…

… all designed for high energy operation.

RF system installed for 46 GeV, upgraded later.

Luminosity estimates:

Based on experience at other e+e- colliders (scaled with damping rate).

# Design Choices: Radius

| Parameter | Symbol | Value |
|---|---|---|
| Effective bending radius | $\rho$ | 3026.42 m |
| Revolution frequency | $f_{\mathrm{rev}}$ | 11245.5 Hz |
| Length of circumference, $L = c/f_{\mathrm{rev}}$ | $L$ | 26658.9 m |
| Geometric radius $(L/2\pi)$ | $R$ | 4242.9 m |
| Radio frequency harmonic number | $h$ | 31320 |
| Radio frequency of the $RF$-system, $f_{\mathrm{RF}} = h\, f_{\mathrm{rev}}$ | $f_{\mathrm{RF}}$ | 352 209 188 Hz |

Synchrotron radiation loss $U_0$ per turn ($e^+/e^-$):

$$U_0 \propto \frac{E^4}{\rho}$$

*For example:*

At 104 GeV ~ 3% of beam energy lost per turn

→ Large radius.

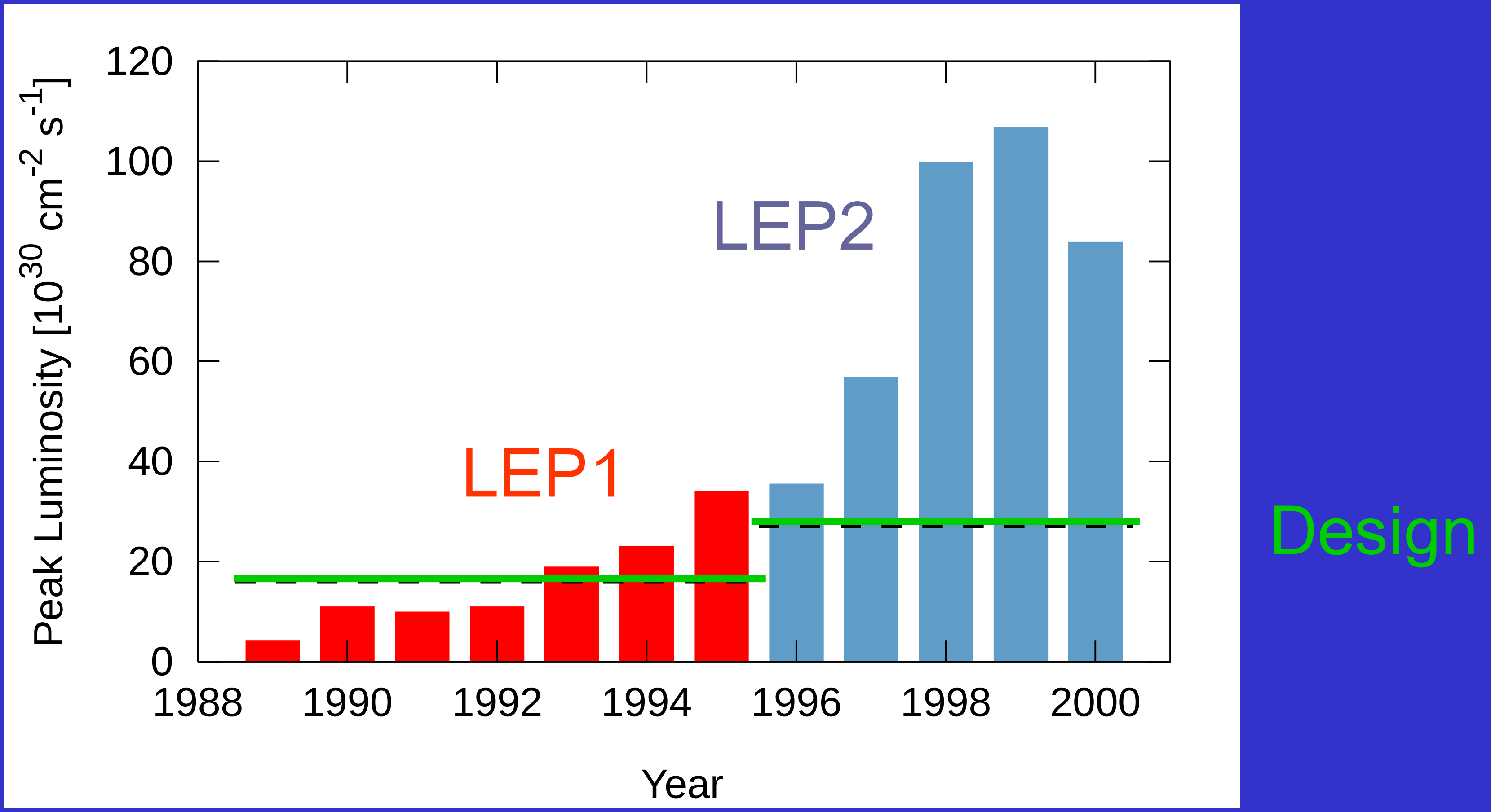
Still:
$V_{rf}$ ~ 3.6 GV for 104 GeV.
World's largest SC RF system

# LEP: Design and Reality

| Parameter | Design (55 / 95 GeV) | Achieved (46 / 98 GeV) | |
|---|---|---|---|
| Bunch current | 0.75 mA | 1.00 mA | |
| Total beam current | 6.0 mA | 8.4 / 6.2 mA | |
| Vertical beam-beam parameter | 0.03 | 0.045 / 0.083 | |
| Emittance ratio | 4.0 % | 0.4 % | 10 times better |
| Maximum luminosity | 16 / 27 $10^{30}$ $cm^{-2}s^{-1}$ | 23 / 100 $10^{30}$ $cm^{-2}s^{-1}$ | x 1.4 / 3.7 |
| IP beta function $\beta_x$ | 1.75 m | 1.25 m | |
| IP beta function $\beta_y$ | 7.0 cm | 4.0 cm | |

Reality always better than design (result of many years work)!

# Peak Luminosity




LEP1: Very realistic design estimates (well-known regime)

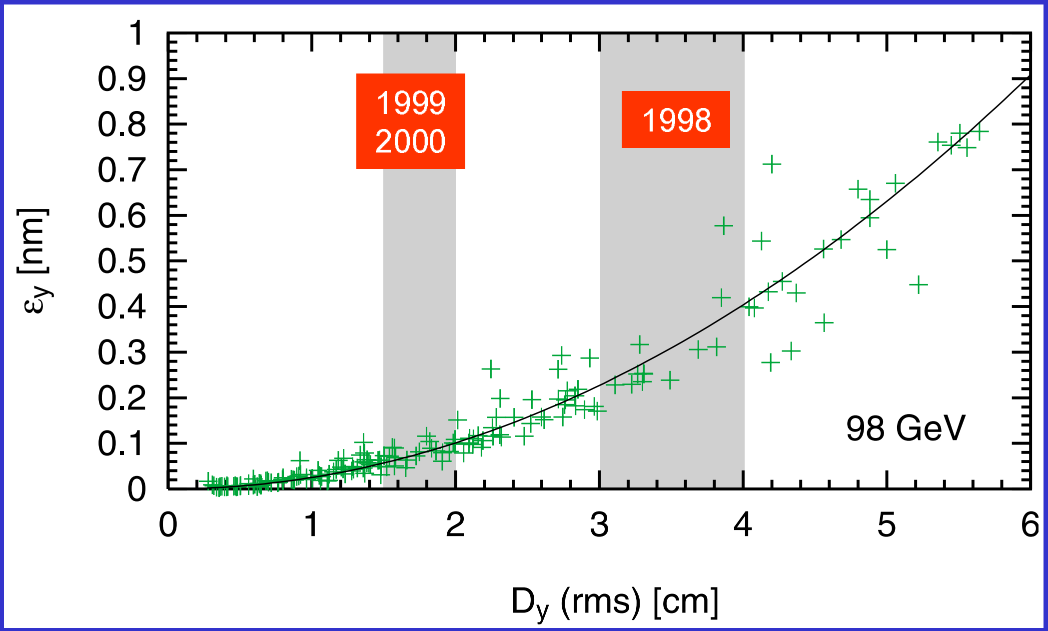
LEP2: Benefits from strong synchrotron radiation damping (too risky to put into design)

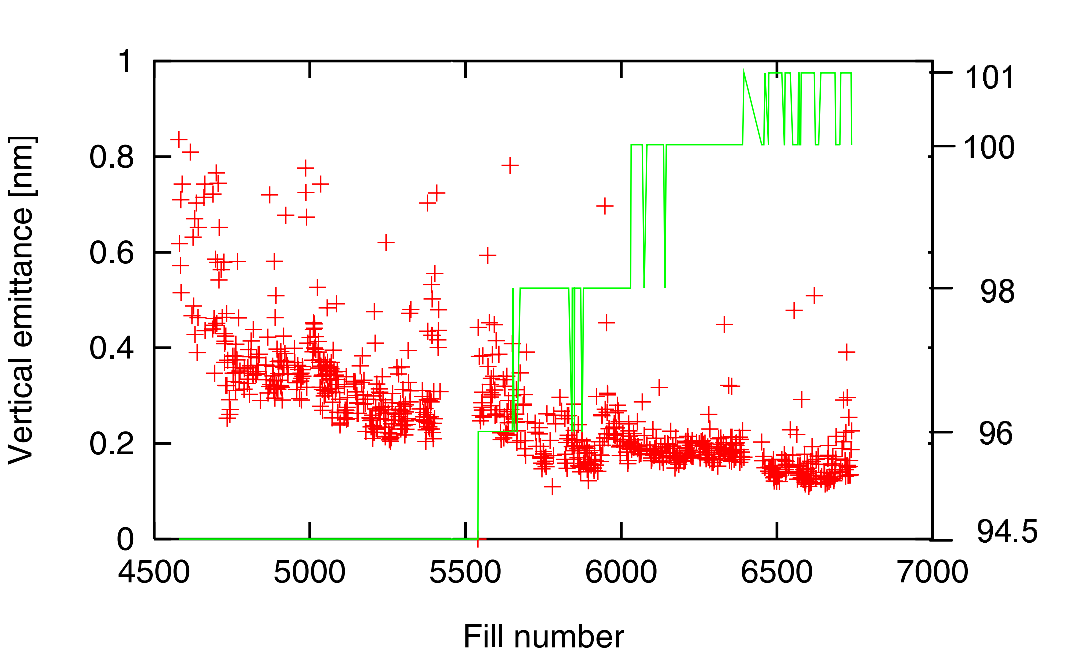
# Vertical Optimization

Reduction of RMS dispersion

(DFS + change of separation optics)

(simulated)



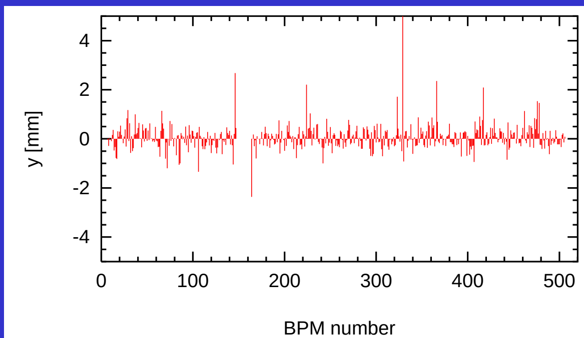



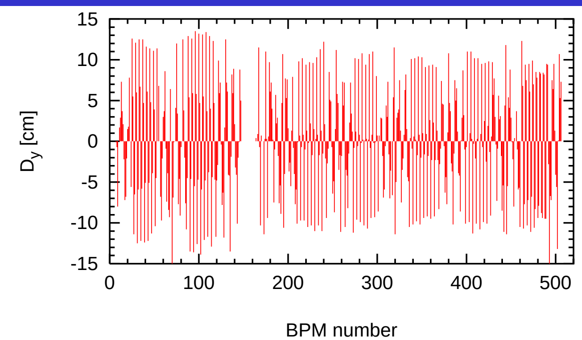

Reduction of vertical emittance

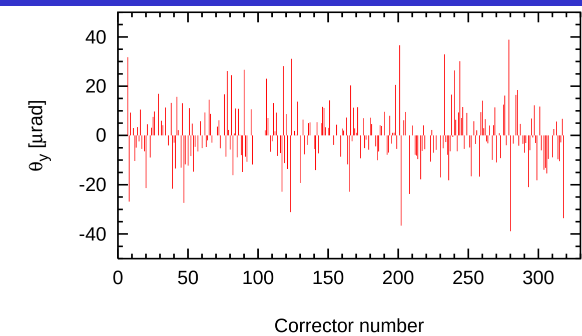
Emittance ratio: 0.5%

# Measured Single Beam Performance of DFS in LEP

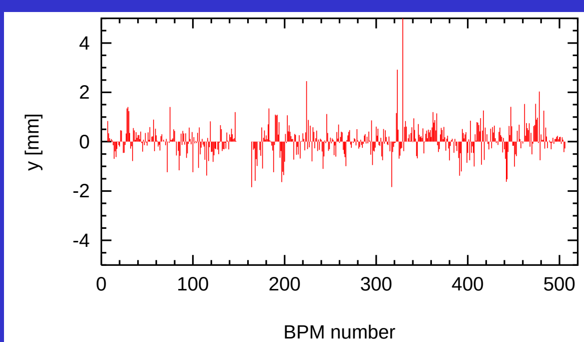
ORBIT | DISPERSION | CORR. KICKS

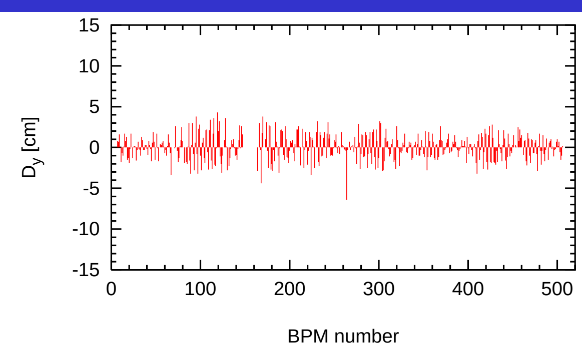


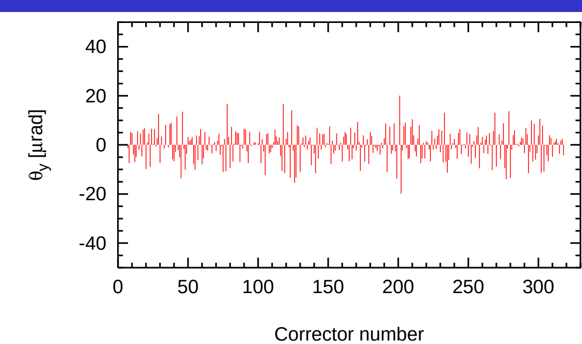




DFS: ⇩ Simultaneously ⇩ optimize orbit, disp., ⇩ corr.



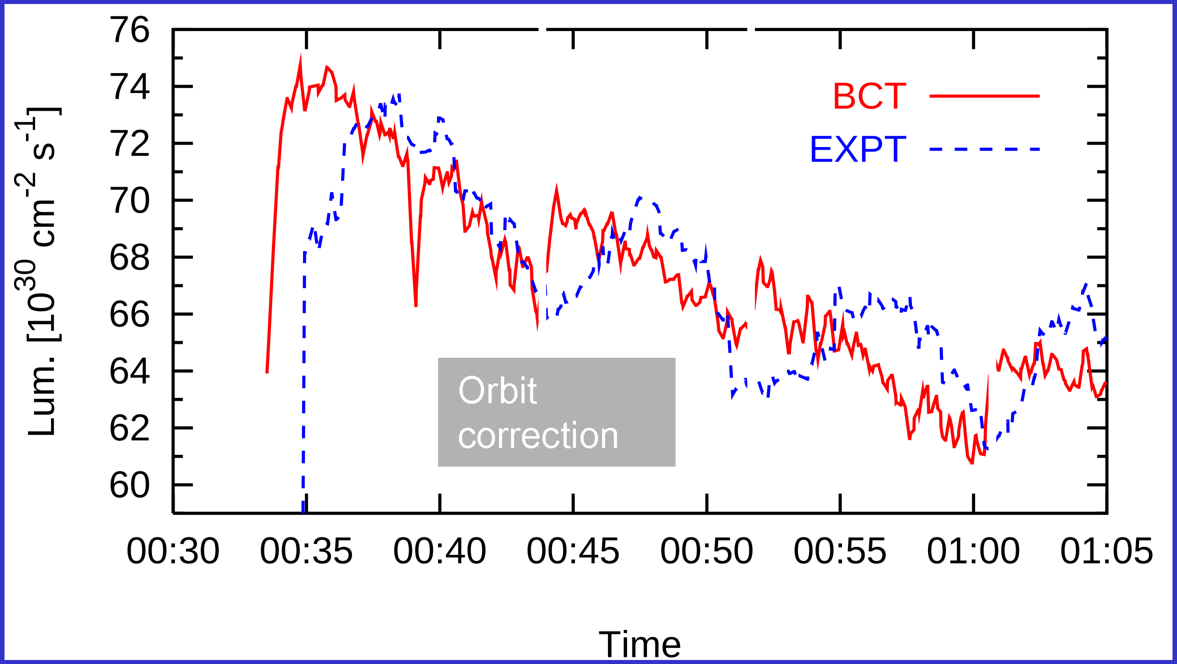




Method developed at linear collider SLC!

Visualize 2D image of LEP2 beam at IP:

# Luminosity Stability (vertical orbit drifts)




$\Delta L \approx 0.3 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per minute

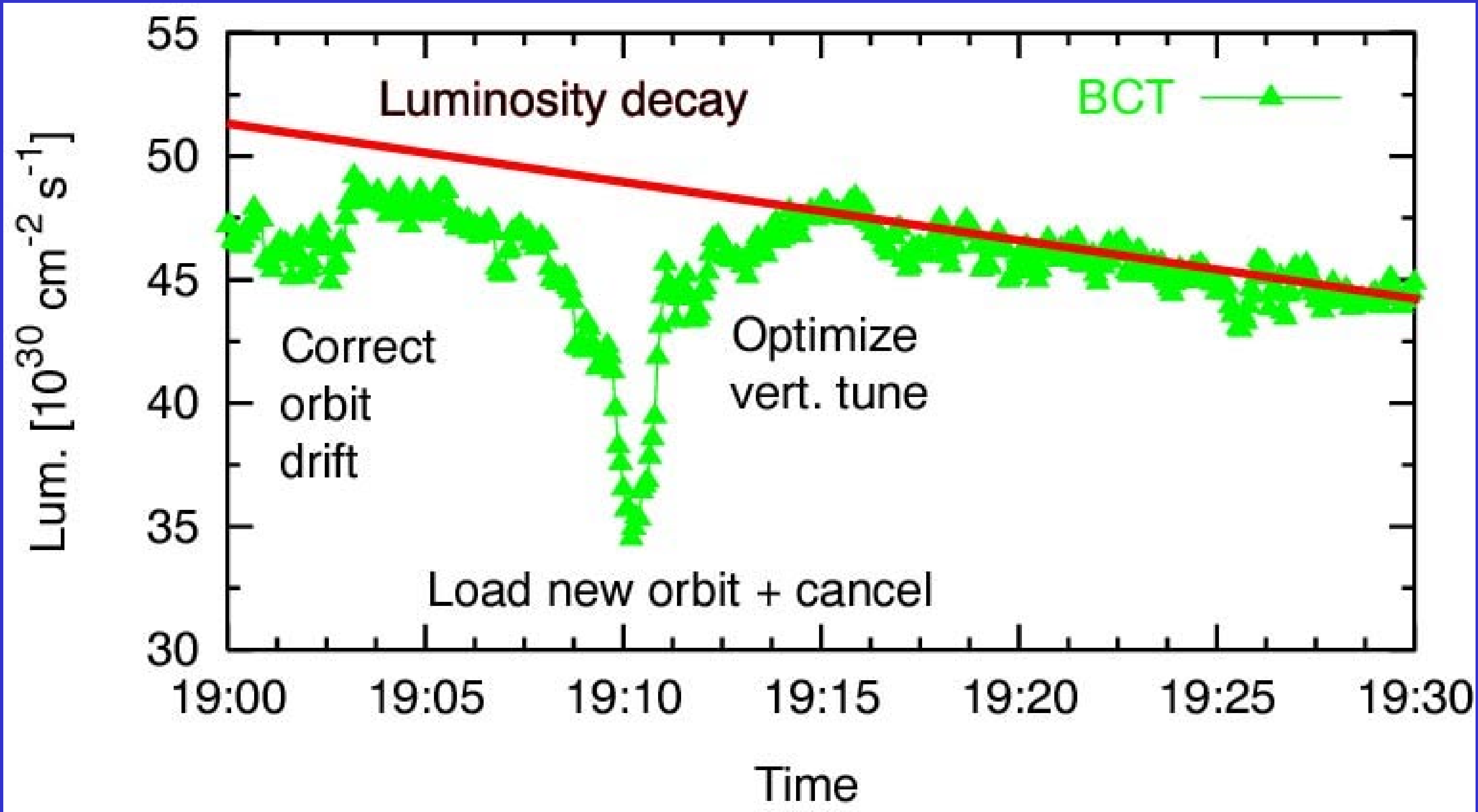
$\Delta \varepsilon \approx 0.002\ \mathrm{nm}$ per minute

$\Delta\varepsilon/\varepsilon \sim 1.5\ \%\ /\mathrm{min}$

Luminosity stabilized with the automatic vertical orbit feedback (“autopilot”) every 7-8 minutes (3% effect).

Both visible from experiments and beam lifetime BCT (faster)!

# Example of Empirical Luminosity Tuning

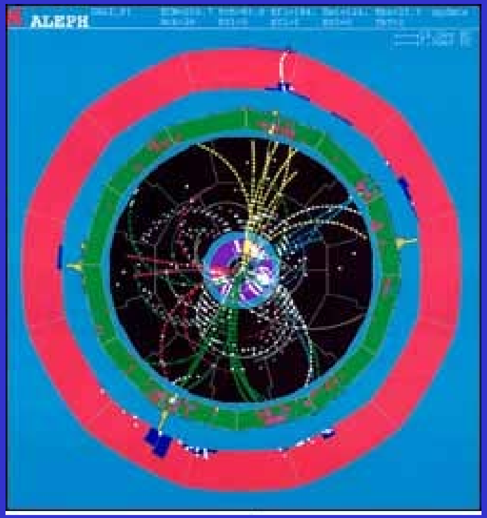


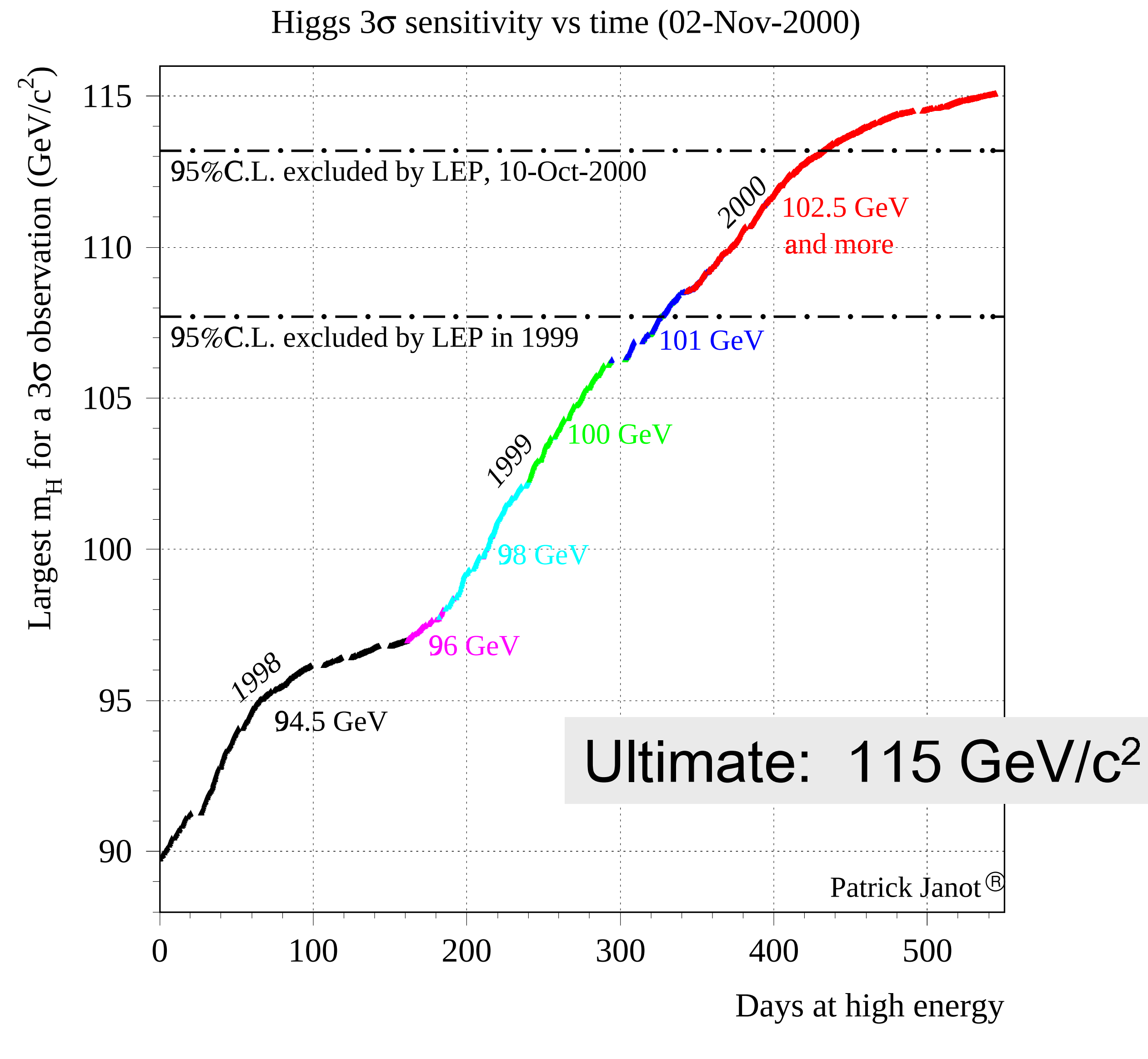

Deterministic and empirical optimization!

# Energy Reach and the Higgs

Luminosity
+
Energy

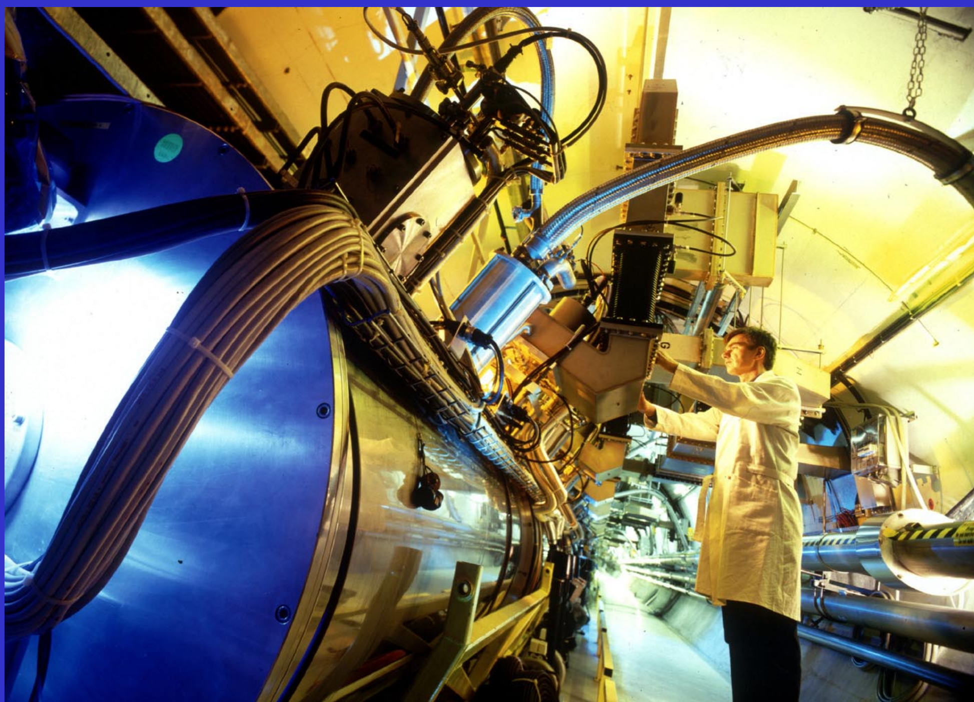
Discovery reach for the Higgs




Ultimate: 115 GeV/$c^2$

# The LEP SC RF System



LEP RF status ON OFF ABNORMAL BUSY 09/10/99 17:14:07

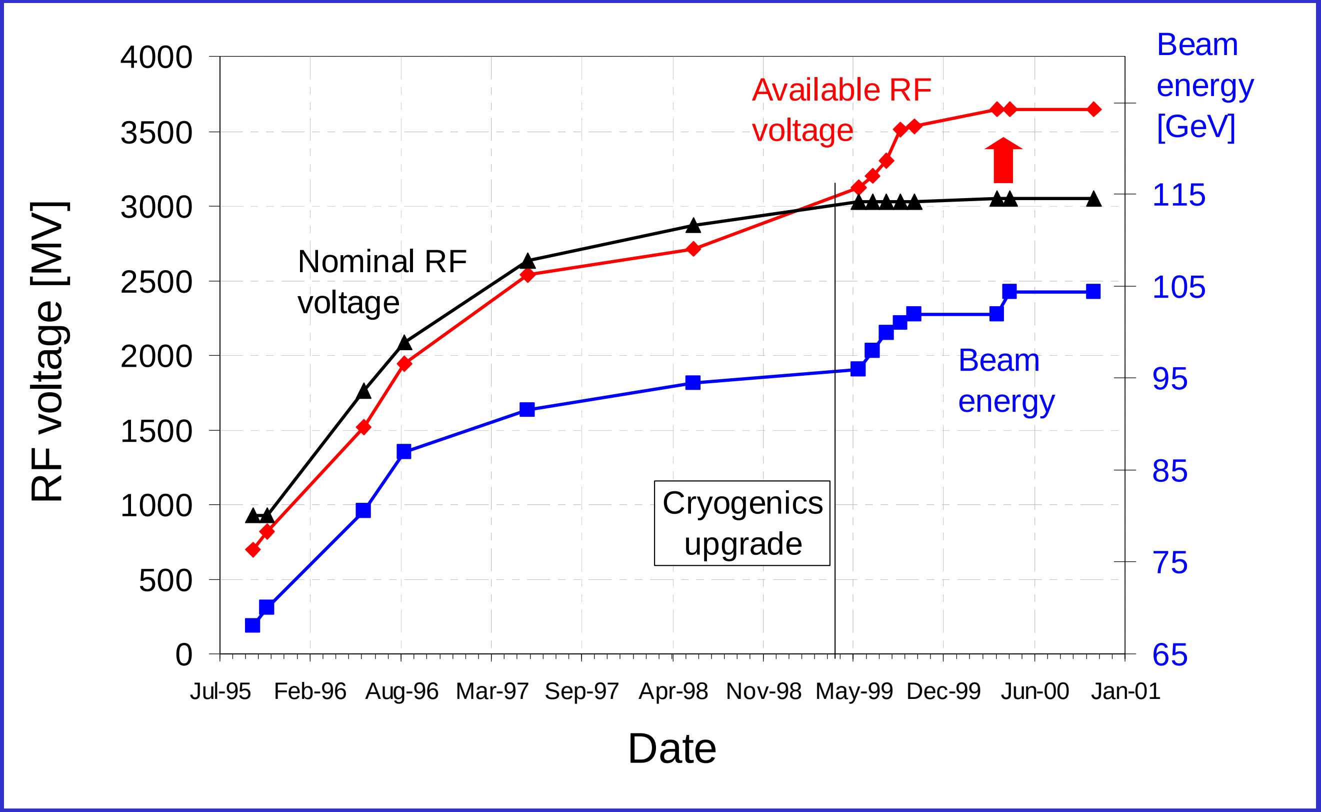
| Unit | Heatrs | HV/kV | K1f/kW | K1r/kW | RF1/MV | K2f/kW | K2r/kW | RF2/MV |
|---|---|---|---|---|---|---|---|---|
| 231 | ON | 77.3 | 484.0 | 5.6 | 24.9 | 515.9 | 2.7 | |
| 271 | ON | 77.3 | 581.9 | 0.0 | 28.9 | 557.1 | 0.8 | |
| 631 | ON | 82.3 | 685.4 | 2.9 | 29.0 | 775.0 | 5.9 | |
| 671 | ON | 77.0 | 651.6 | 5.1 | 27.6 | 608.4 | 8.0 | |
| 232 | ON | 82.1 | 565.7 | 250.0 | 99.4 | 453.3 | 154.0 | 99.4 |
| 233 | ON | 82.6 | 394.3 | 112.5 | 99.9 | 459.0 | 67.4 | 88.2 |
| 272 | ON | 82.1 | 636.9 | 248.2 | 99.3 | 660.5 | 275.9 | 99.2 |
| 273 | ON | 82.1 | 248.8 | 82.4 | 57.2 | 246.1 | 58.0 | 57.4 |
| 431 | ON | 81.5 | | | | 454.7 | 164.2 | 97.3 |
| 432 | ON | 82.9 | 388.5 | 92.1 | 100.1 | 408.2 | 147.7 | 99.8 |
| 433 | ON | 82.0 | 269.6 | 168.3 | 91.2 | 396.8 | 121.5 | 97.5 |
| 471 | ON | 81.5 | 439.4 | 181.1 | 96.2 | | | |
| 472 | ON | 81.6 | 393.7 | 133.5 | 96.3 | 406.7 | 156.5 | 89.5 |
| 473 | ON | 81.3 | 388.7 | 126.1 | 94.8 | 298.1 | 162.9 | 80.8 |
| 632 | ON | 82.0 | 580.8 | 215.5 | 100.4 | 367.0 | 193.4 | 99.0 |
| 633 | ON | 82.2 | 522.2 | 237.9 | 95.8 | 396.3 | 133.3 | 99.2 |
| 672 | ON | 82.1 | 430.0 | 158.5 | 100.0 | 494.4 | 205.4 | 94.3 |
| 673 | ON | 81.7 | 536.8 | 142.6 | 95.7 | 510.8 | 144.1 | 94.8 |
| 831 | ON | 82.0 | | | | 443.3 | 160.4 | 101.0 |
| 832 | ON | 82.0 | 405.4 | 123.8 | 101.7 | 408.0 | 104.5 | 102.4 |
| 833 | ON | 82.1 | 361.6 | 176.4 | 101.1 | 405.6 | 164.9 | 104.0 |
| 871 | ON | 82.0 | 520.8 | 195.1 | 101.2 | | | |
| 872 | ON | 81.8 | 423.0 | 103.6 | 101.0 | 390.2 | 108.5 | 102.8 |
| 873 | ON | 82.1 | 450.0 | 129.3 | 106.6 | 438.1 | 218.4 | 94.7 |

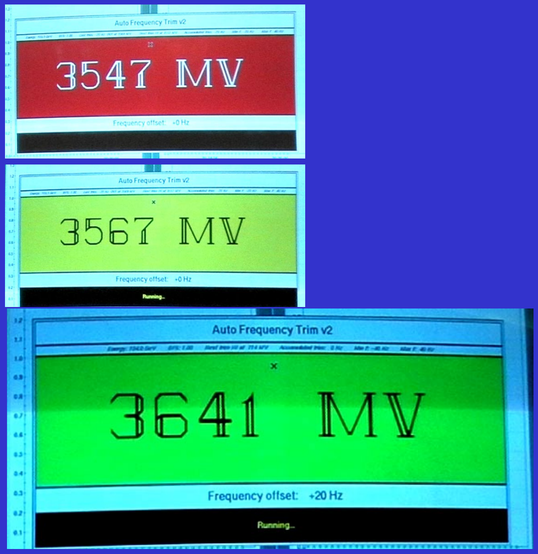
Total MV 3550

1 klystron = 2 modules
= 8 cavities
= 13.6 m
~ 97 MV

Operation cares about:
Available RF voltage
Especially trip rate

# Available RF Voltage




| Beam energy (year) | Average accelerating field [MV/m] |
|---|---|
| 96 GeV (1999) | 6.1 |
| 100 GeV (1999) | 6.9 |
| 104 GeV (2000) | 7.5 |

Design:

6 MV/m

# Trip Rate and Fill Length

Big system:

- 36/8 klystrons (SC/Cu)
- 288/56 cavities (SC/Cu)
- 53 kW cooling power (He 4.5K)
- ~ 10000 interlocks

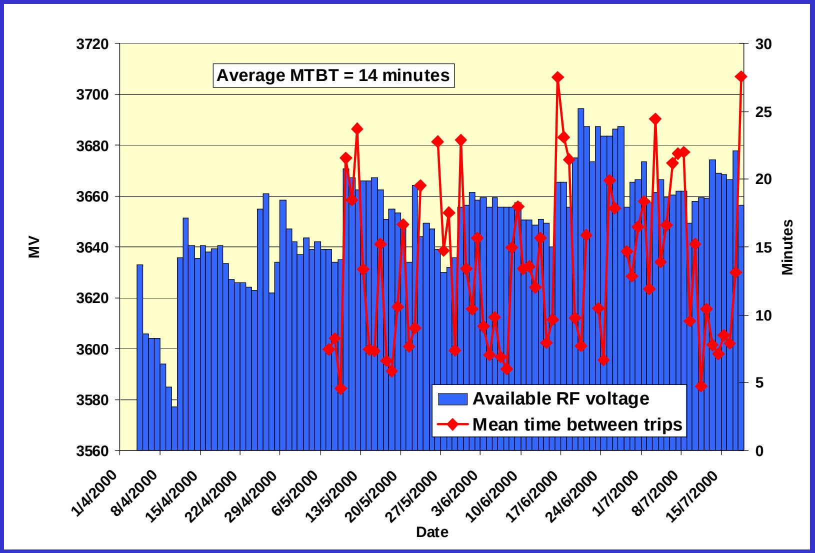
Performance:

RF voltage pushed to limit (~ 3650 MV)
Limit defined as acceptable trip rate

Trips caused by:

Equipment failures (a few % of trips)
Running at field levels at performance limit
Field emission ➢ Helium pressure rise ➢ Quench
Cryogenics stability (He pressure rise / He level)
Coupling between units via the beam at high current

| Beam energy | Length of physics fill |
|---|---|
| Maximum | 14 min |
| Maximum – 0.8 GeV | ~ 1.5 hours |
| Maximum – 1.6 GeV | Set by dump |

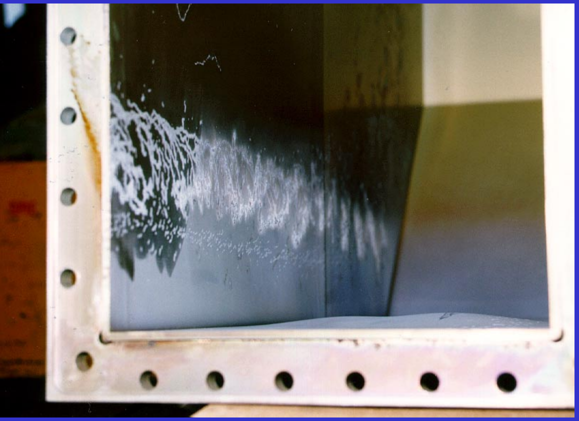


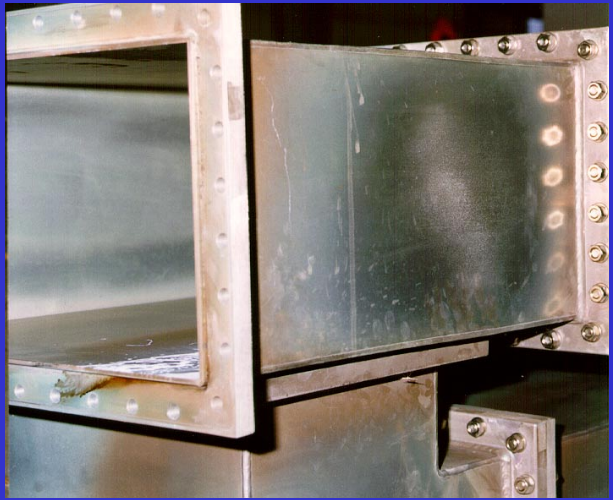
# Damage in the RF System

*Damage in waveguides*
*(Transport of RF power from klystrons to cavities)*

*Empirical limit for total beam current: ~ 5 mA*

Origin: *Beam-induced electro-magnetic fields (HOM), RF power*
Damage: *Heating, deformation, holes*





*High energy operation of LEP left its marks…*

*We did something right, but it still worked beautifully...*

Lost 4 out of 288 cavities (40 - 50 MV)

# Spin Polarization in LEP

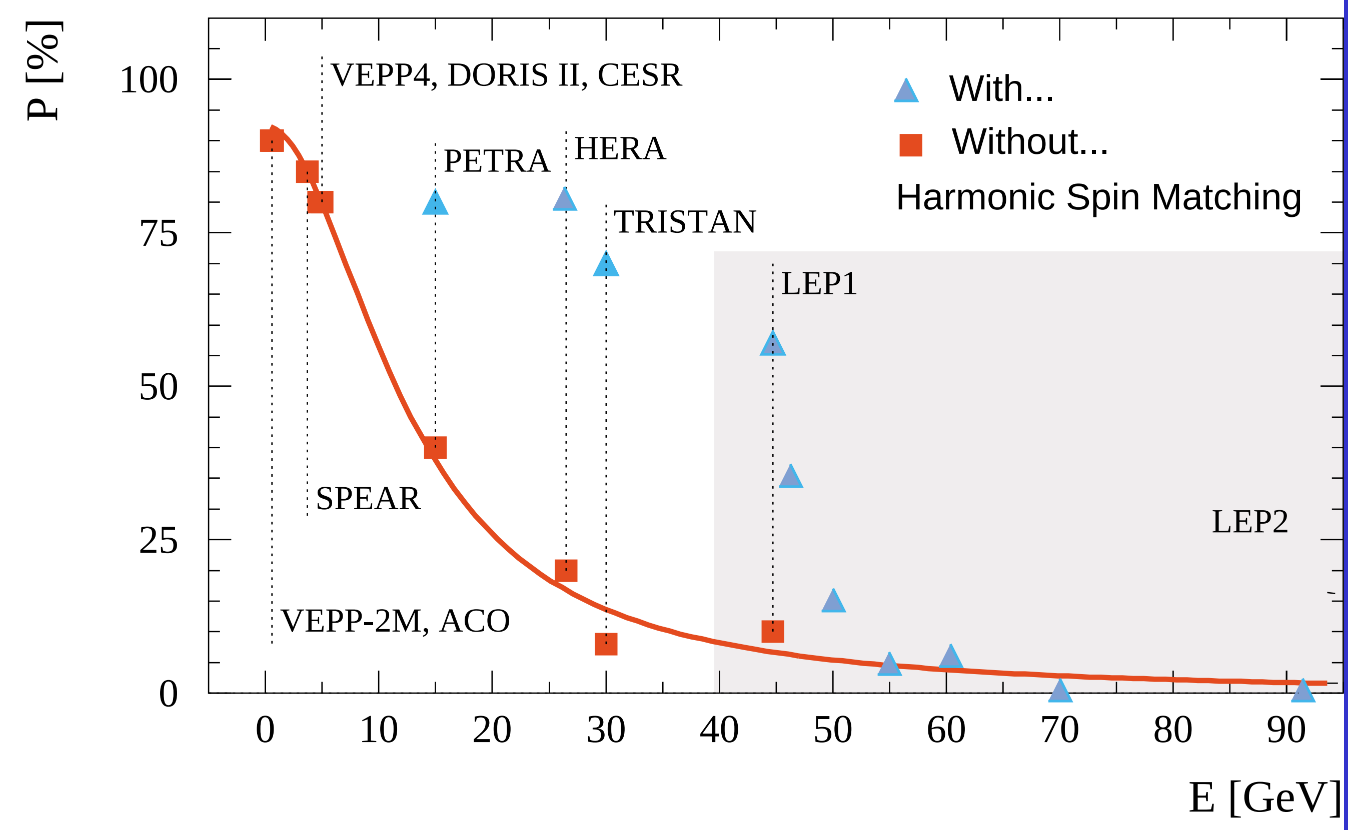
Unique at LEP:

| | | | |
|---|---|---|---|
| Large range of energies | 22 GeV | to | 104.5 GeV |
| Polarization studied from | 41 GeV | to | 98.5 GeV |

Explore spin dynamics in unique regime

Bench marking of theoretical predictions

Sharp drop-off!



# Verification of Theory

Theory by Derbenev, Kontratenko, Skrinsky (with LEP Parameters):

Spin tune $\nu = \dfrac{E}{440.6486\,\mathrm{MeV}}$

Polarization buildup rate $\lambda = \dfrac{1}{\tau_p} = 3.9 \cdot 10^{-19} \cdot \nu^5$

Synchrotron tune $\nu_\gamma$

Spin tune spread $\sigma_\nu = \nu \cdot \dfrac{\sigma_E}{E} \approx 6.67 \times 10^{-6} \cdot \nu^2$

Resonance strength $|w_k|^2 \approx 1.94 \times 10^{-10} \cdot \nu^2$

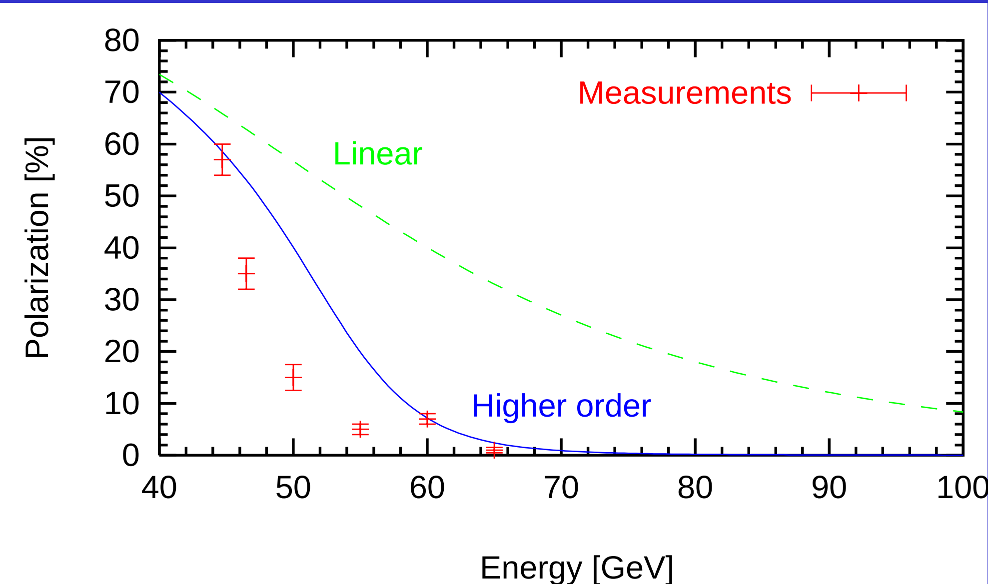
Condition for correlated spin resonance passings: $\alpha = \dfrac{\nu^2 \lambda}{\nu_\gamma^3} << 1$

true

$$\frac{\tau_p}{\tau_d} = \frac{11}{18} \nu^2 \sum_{k,m} \frac{|w_k|^2 \left\langle T_m^2(\Delta/\nu_\gamma) \right\rangle}{\left[ \left(k - \bar{\nu} - m\nu_\gamma\right)^2 - \nu_\gamma^2 \right]^2}$$

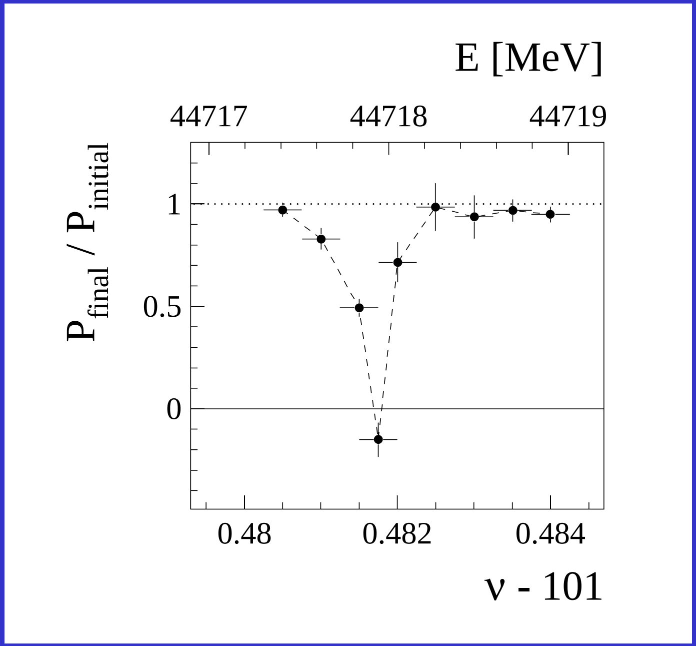
$$\left\langle T_m^2 \right\rangle = I_m\left(\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right) \cdot \exp\left(-\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right)$$

First confirmation!

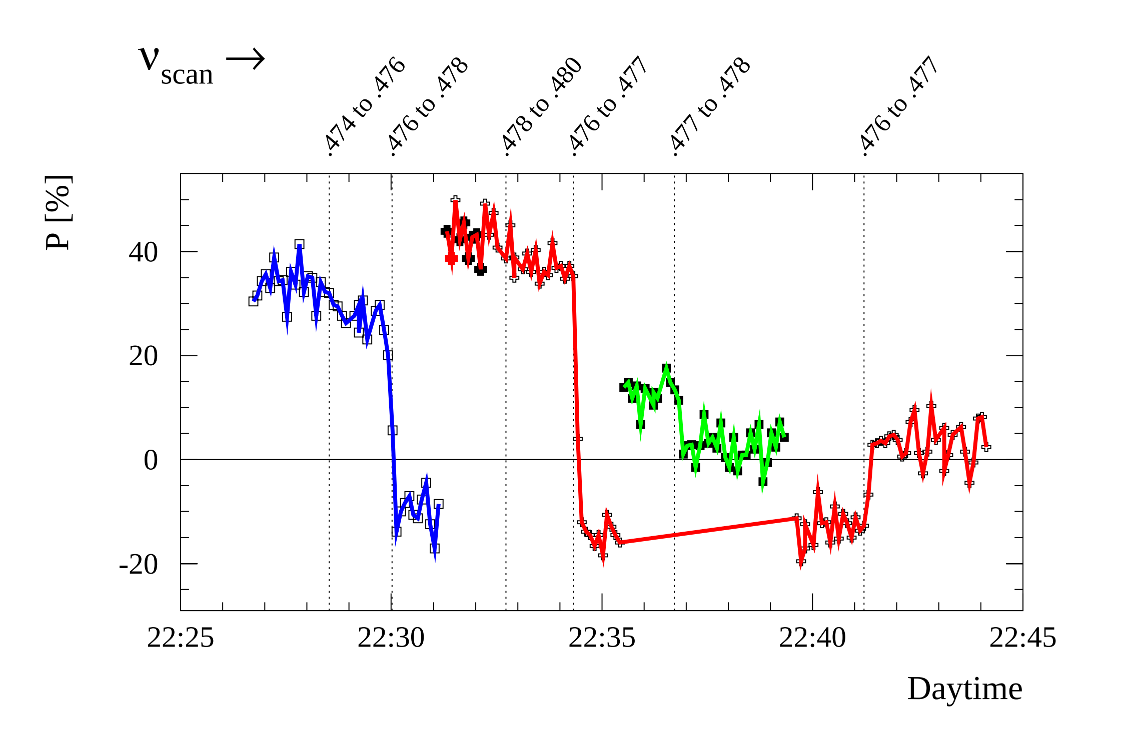


# Energy Calibration

## by resonant depolarization

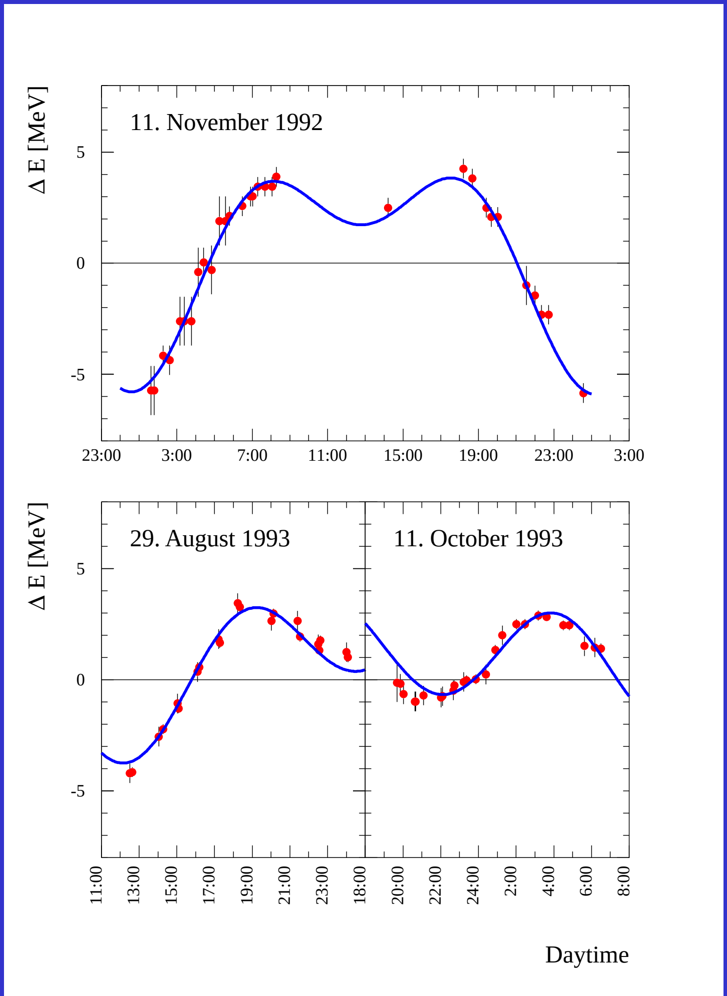


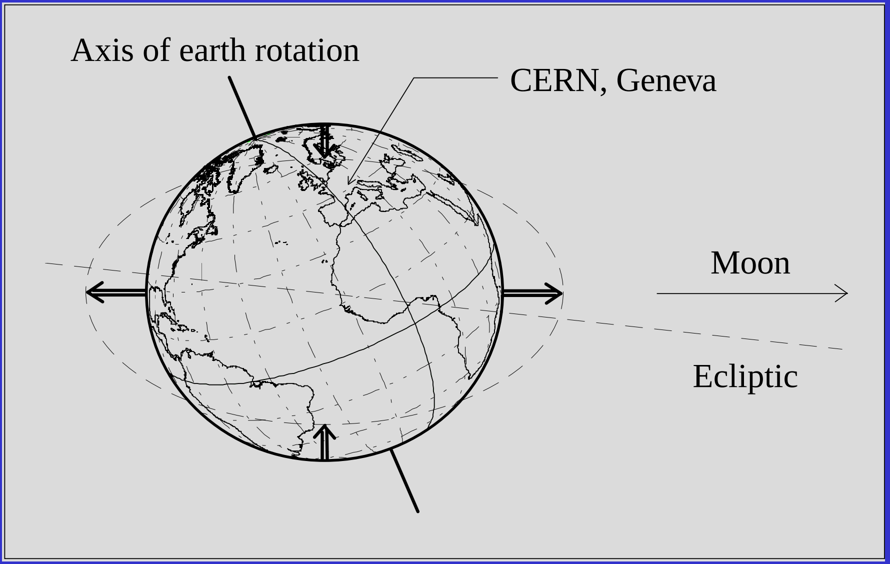

Half-width of resonance: 150 MeV



# Unexpected I: The Earth Tides

Precise determination of the LEP beam energy (${10^{-5}}$ relative accuracy, ~ 1 MeV)
Precise measurement of the Z mass and width



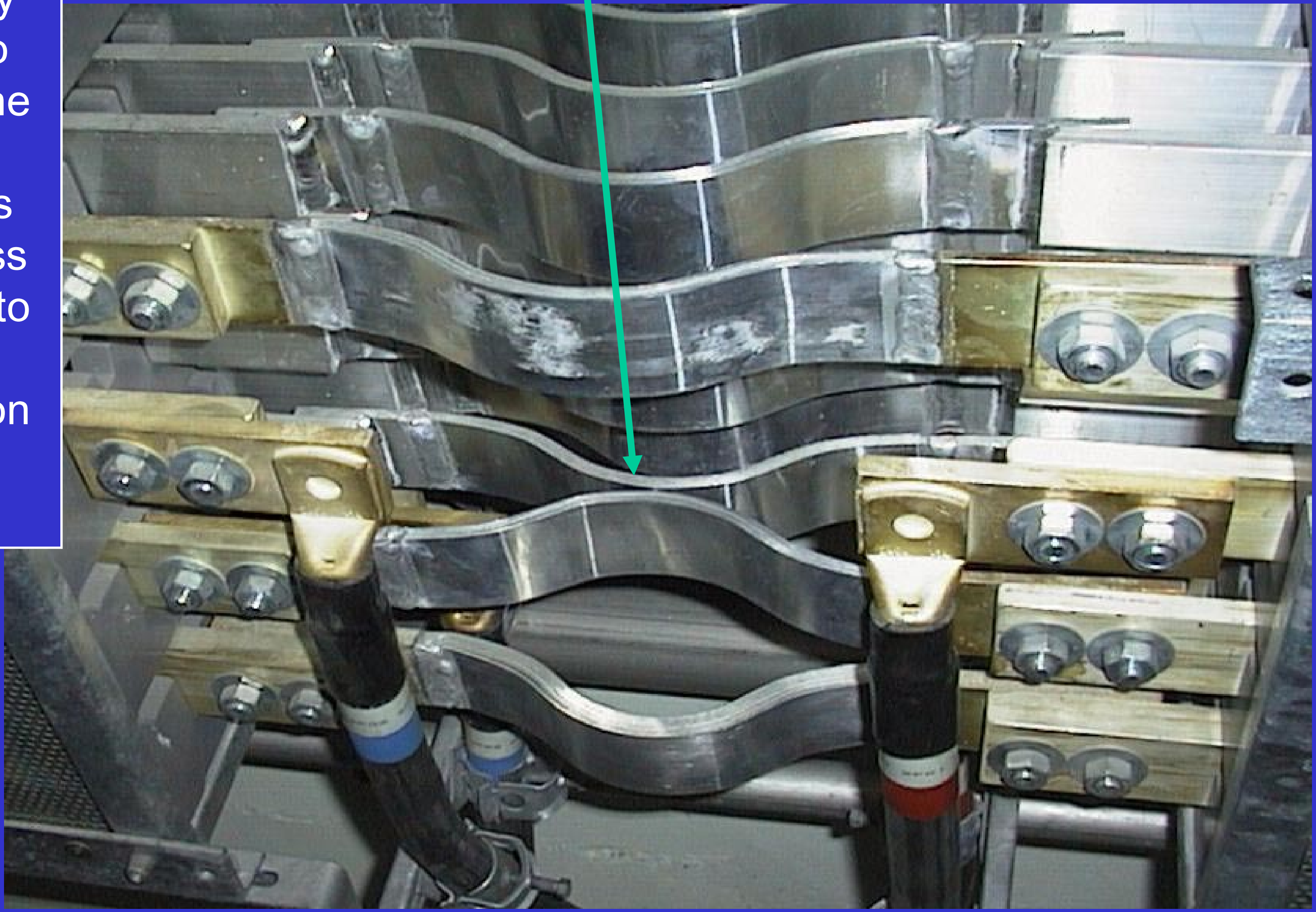

Small changes of energy accurately measured
*(energy change for 1mm circumference change)*

LEP energy affected by:

Tides, water levels, train currents (TGV)

# Unexpected II: Sextupole Trips

LEP repeatedly trips after 10 to 30 minutes. The time between trips decreases with time unless you do not try to switch on. Problem was on the sextupole chains

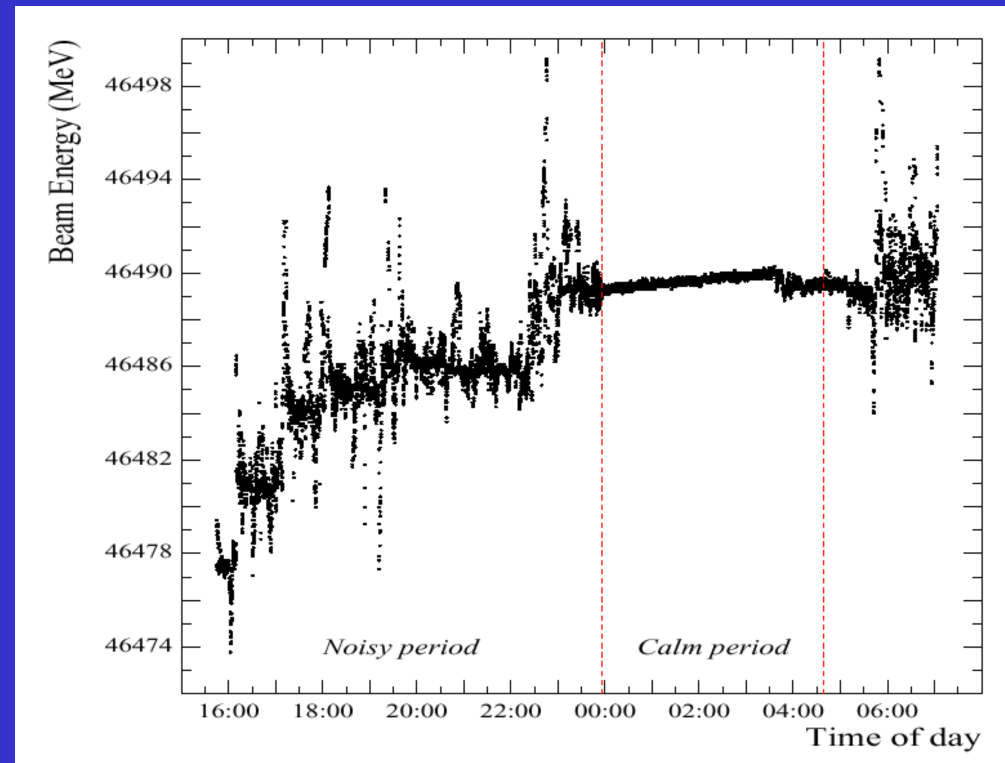


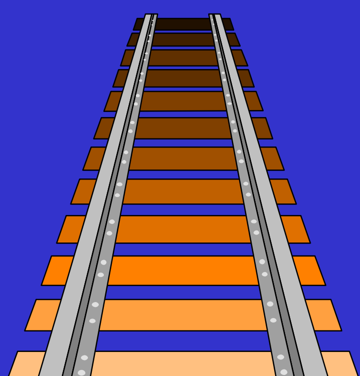
# Unexpected III: LEP and the Fast Train

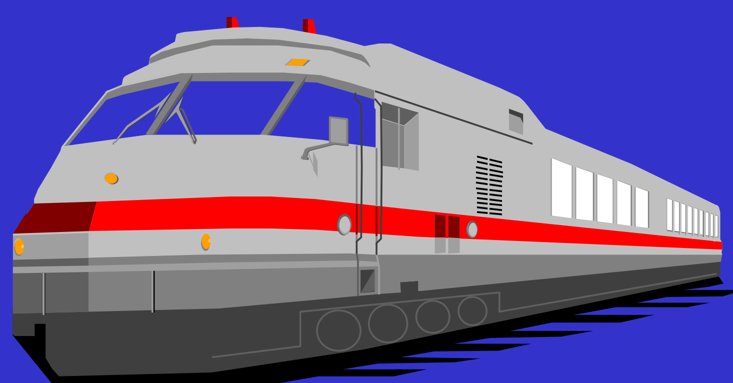
Influence on the beam energy

- the moon, sun and tides
- the level of lake Geneva
- the amount of rain

AND the fast train.........

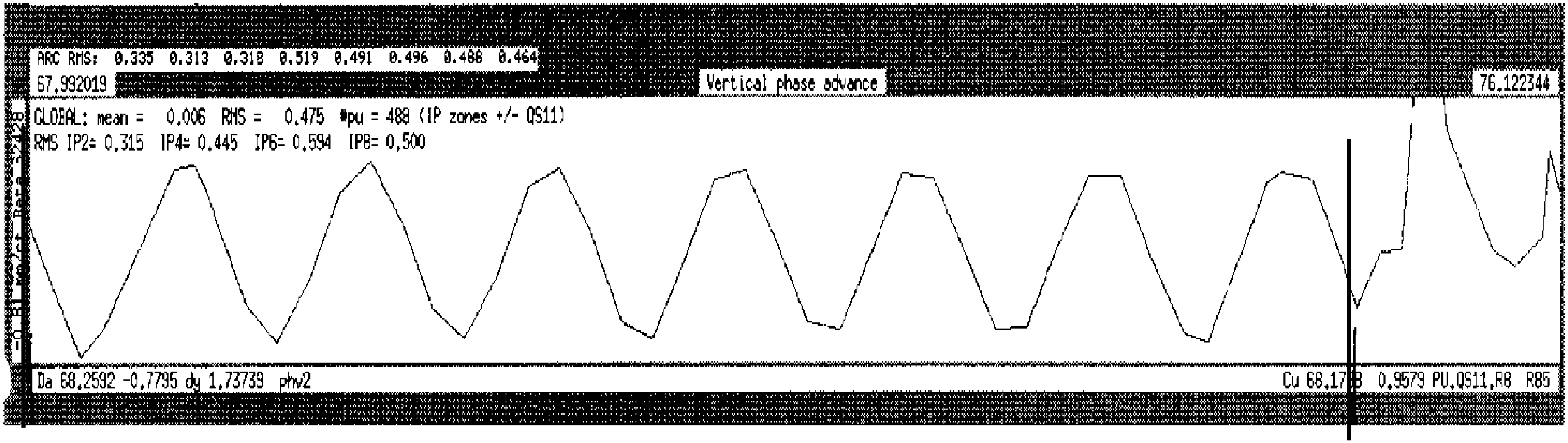




# Unexpected IV: The Beer Bottles

Could not get the beam to circulate more than 15 turns even with large bumps all around the ring. Use single turn orbit system and normalised the measurement.

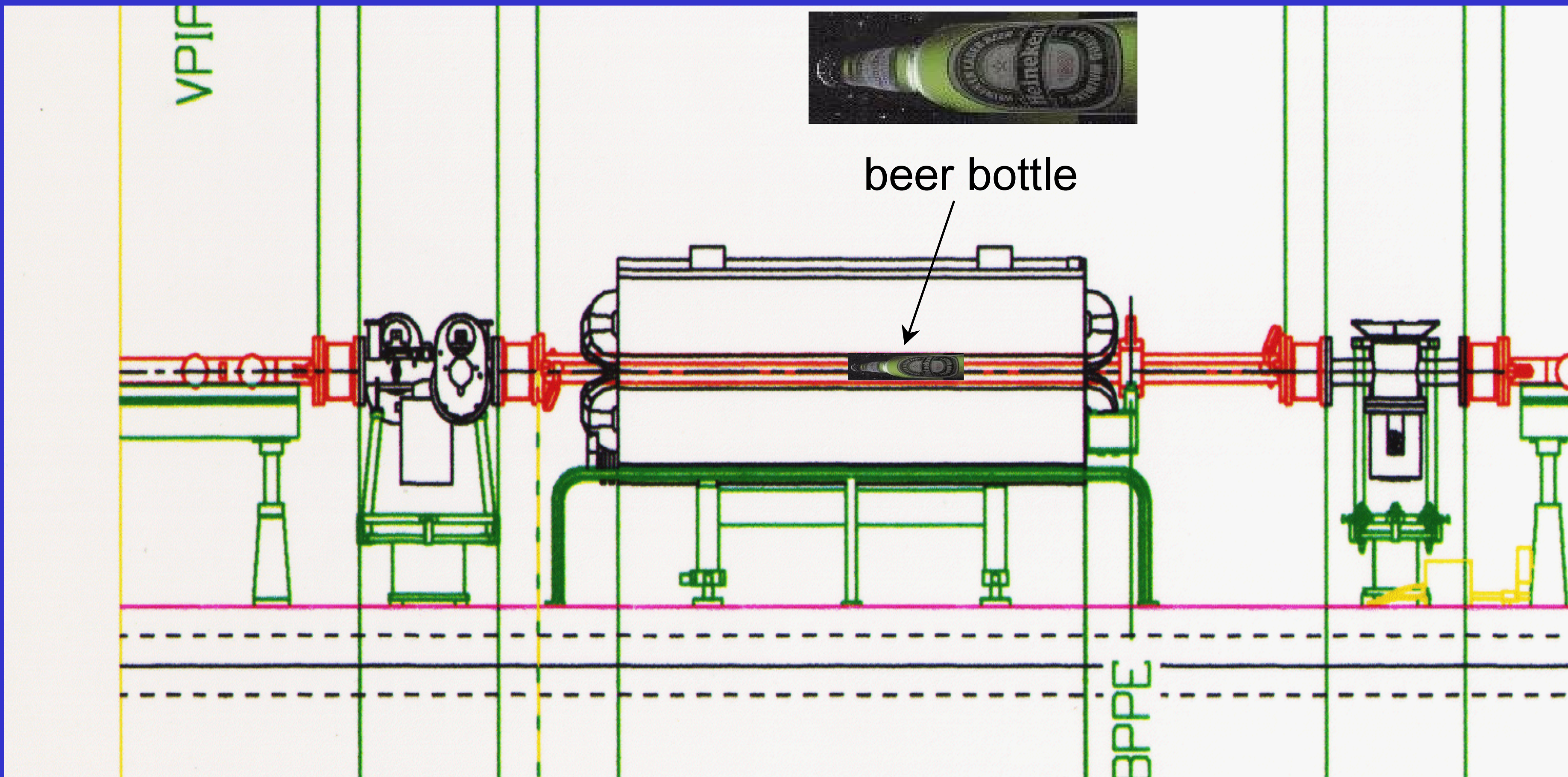



Single Turn
Stopper

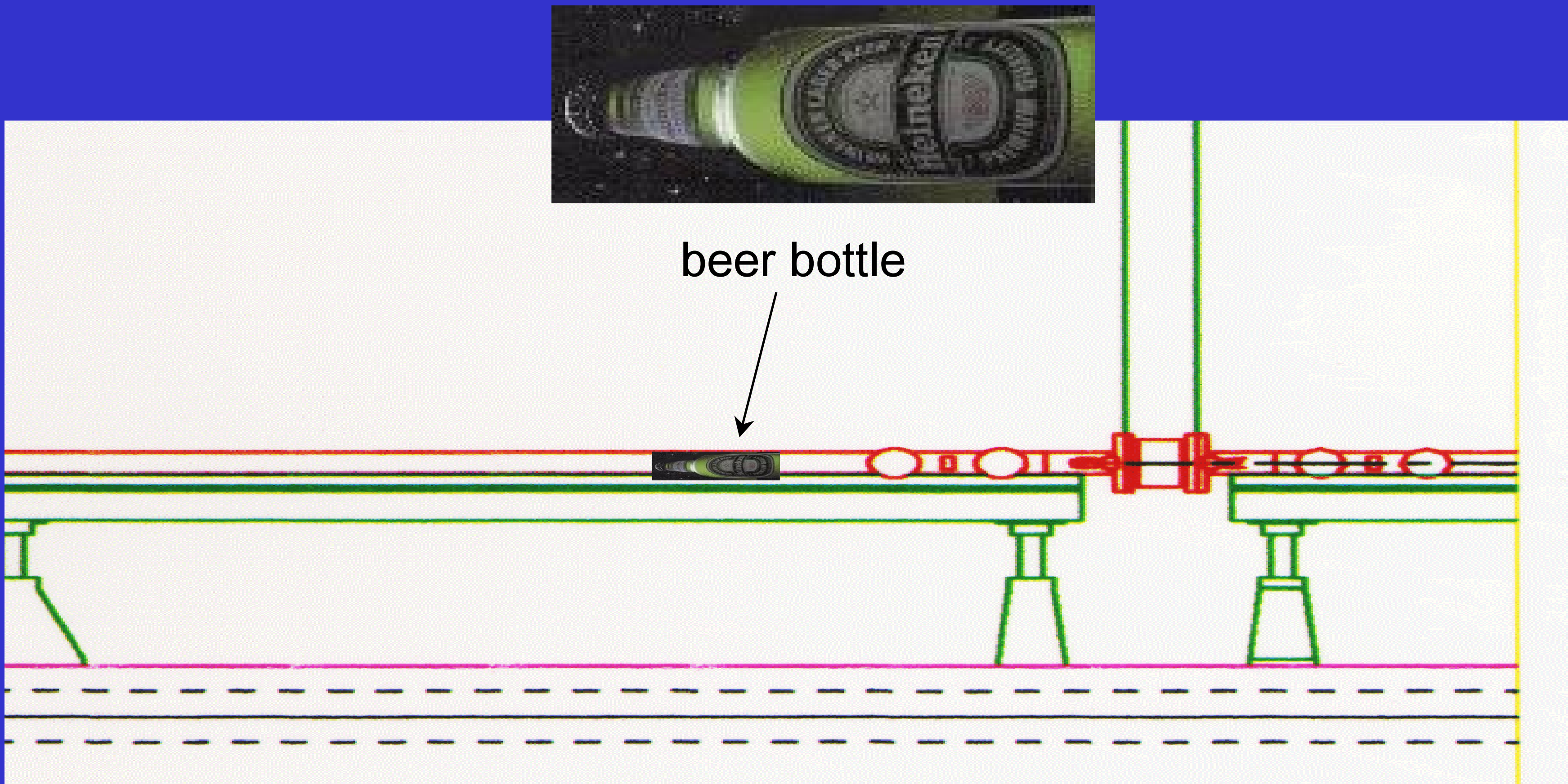
positrons

QL10.L1

# Zoom in on Quadrupole

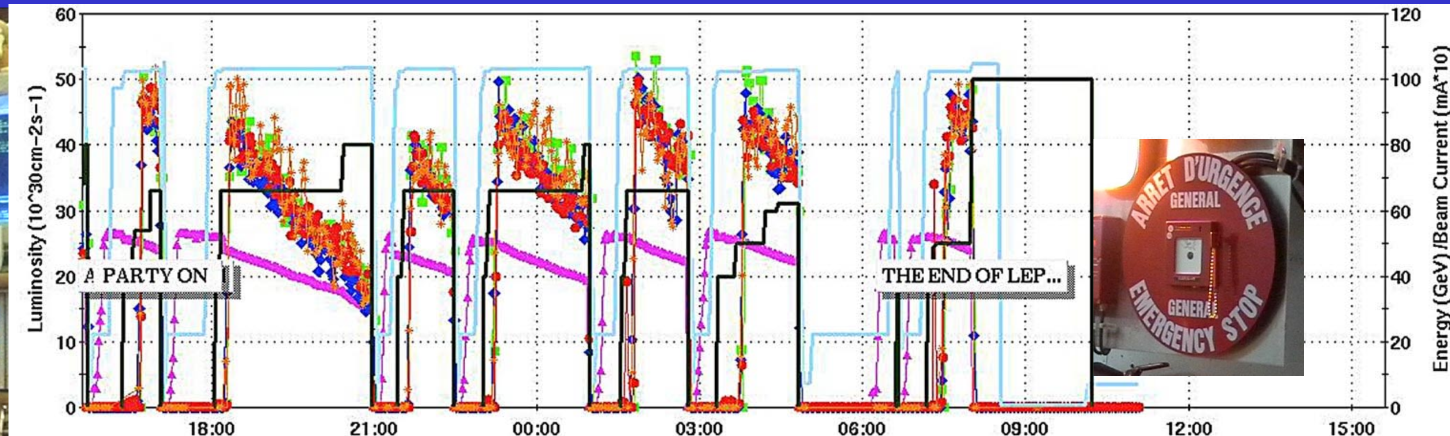


# 10 Metres to the Right




Unsociable sabotage: both bottles were empty!!

# The End of LEP …





November 2$^{nd}$, 2000, 7am

# Outline

- Energy and Luminosity
  The measure of success in particle physics
  Limitations and our job (the challenge)
- SLC – Controlling collective effects in the linac
  The linear collider
  The SLC linac beam (layout, beam movies)
  Wakefield emittance growth, Day-night effects, DFS
  The SLC team at SLAC
- LEP – Beating the design
  The LEP team at CERN
  Design and reality
  Vertical beam size optimization (luminosity)
  The super-conducting RF system (beam energy)
  Spin polarization of particle beams
  The unexpected I - IV
- LHC – High intensity proton beams
  The challenge of high beam power
  The beam cleaning and collimation system
- Conclusion

# The LHC Beam

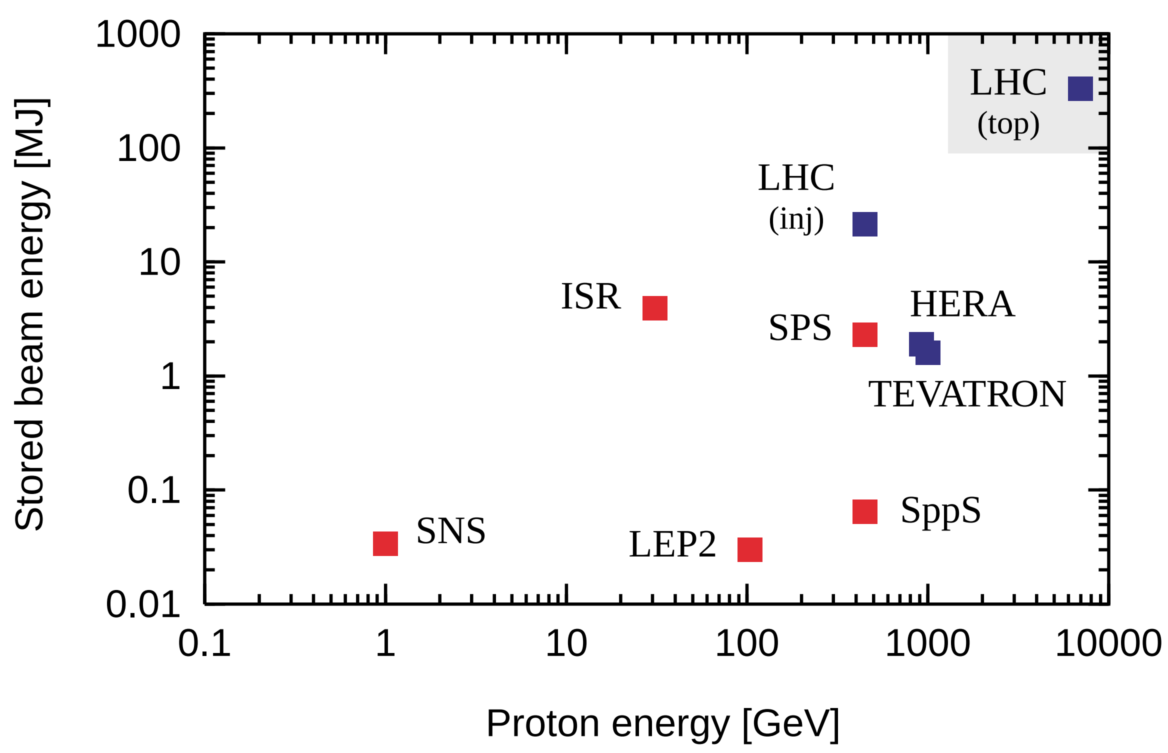
Number of bunches: 2808
Bunch population: 1.1e11
Bunch spacing: 25 ns

*Top energy:*

Proton energy: 7 TeV
Transv. beam size: 0.2 mm
Bunch length: 8.4 cm
Stored energy: 331 MJ

*Injection:*

Proton energy: 450 GeV
Transv. Beam size: 1 mm
Bunch length: 18.6 cm




Step from previous accelerators:

Factor 7 in proton energy
Factor 100 in stored beam energy

The powerful LHC beam to be handled in sensitive SC environment!

# LHC Beam Cleaning Study Group

Mandate: Study beam dynamics and operational issues for the LHC collimation system. Identify open questions, assign priorities, and show the overall feasibility of the LHC cleaning system.

R. Assmann (chairman)
I. Baishev
O. Bruening
H. Burkhardt
G. Burtin
B. Dehning
S. Farthoukh
C. Fischer
E. Gschwendtner
M. Hayes
J.B. Jeanneret
R. Jung
V. Kain
D. Kaltchev
M. Lamont
H. Schmickler
R. Schmidt
J. Wenninger

Work in coordination with the Machine Protection Working Group.

Report the LHC Commissioning Committee.

# Main design considerations

1. Machine protection / monitoring signal for losses
   *Intercept perturbed beam at collimators. Protect against quenches/damage.*

2. Durability / hardware robustness
   *Make sure collimators survive beam operation. Avoid lengthy repairs.*

3. Beam cleaning efficiency
   *Remove beam halo in nominal conditions. Protect against quenches.*

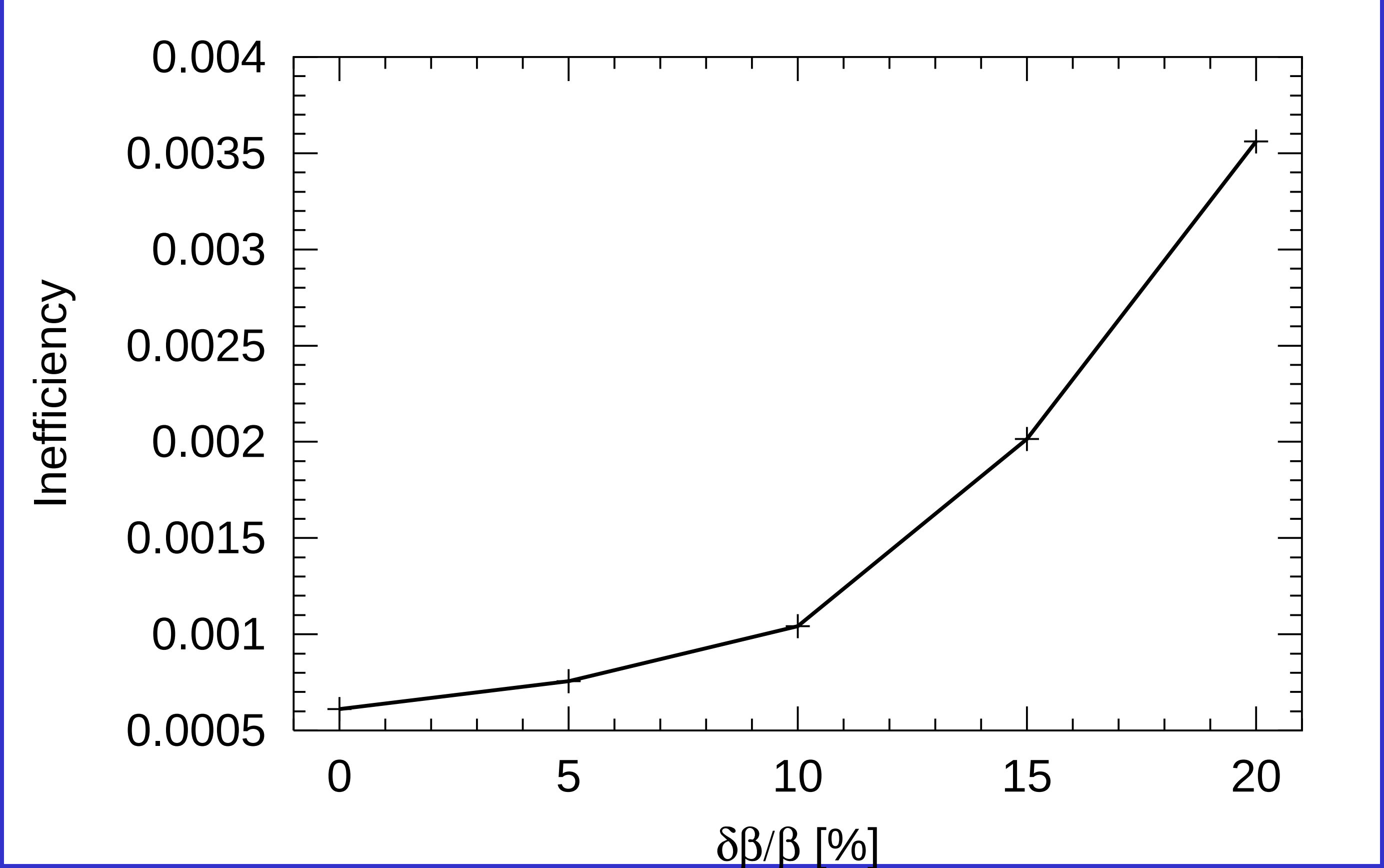
Expected inefficiency in a realistic environment:

| | |
|---|---|
| Beam input: | Beam loss (regular, irregular), emittance, diffusion speed, tunes, … |
| Coll. design input: | Surface flatness, alignment errors, positioning, heating deformations, … |
| Machine imperfections: | Beta beating (on/off momentum), orbit (stability?), coupling, injection oscillations, non-linear fields, … |
| Operational aspects: | Tunability, maintainability, stability, … |

# Effect from transient beta beating

(on-momentum, worst phase)

Change of beta beat without readjustment of collimators (e.g. ramp, squeeze).

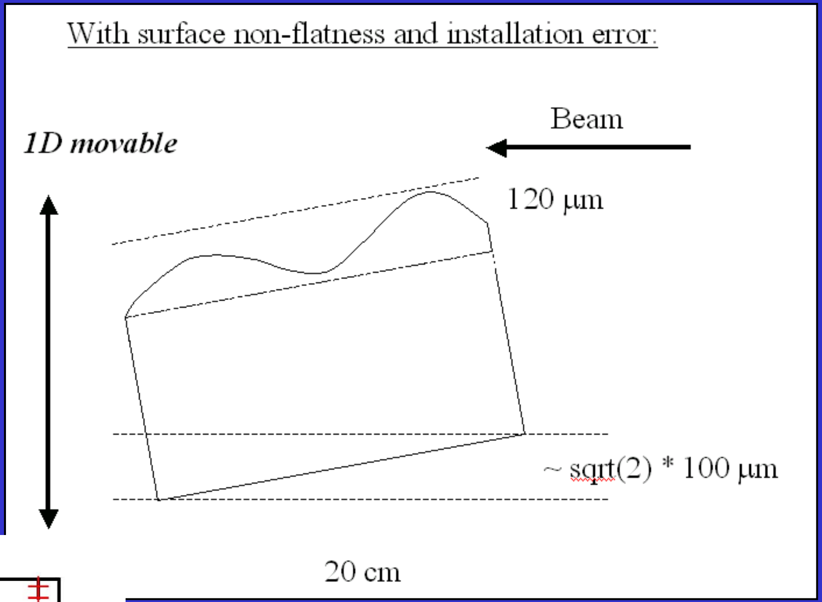



Inefficiency ~ doubles for 10% beta beating.

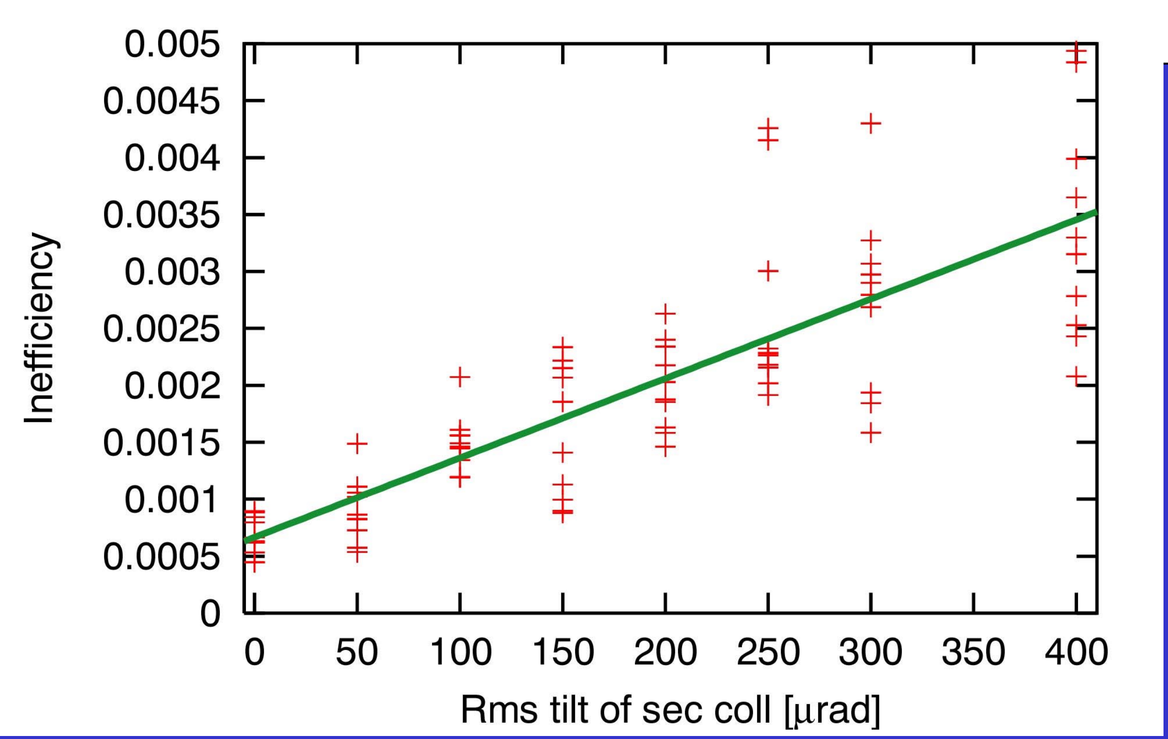
# Tilt of secondary jaws

(all results work in progress)

Randomly tilt secondary jaws
(10 seeds for each angle)




*Input from G. Burtin*




Inefficiency ~ triples for 150 µrad rms tilt. It stays below 0.25%.

*No angle control foreseen!*

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# Conclusion

- Running and optimizing large accelerators is certainly challenging but also lots of fun!
- A good understanding of the relevant accelerator physics is important for a good design (often implies specific research and experiments).
- With a careful design, engineering, and construction (tolerances) the promised performance can be achieved and surpassed.
- There will be unexpected limitations! It is important to have plenty of diagnostics for experimental observations.
- Accelerator physics provides the toolbox to understand these observations and to overcome the limitation.
- But also: Experimental input is often crucial for the progress in accelerator physics.
- From my experience it is beneficial to have accelerator physicists close to the beam. In other words: Put beam physicists close to the beam.